Boundary Integral Equations on the Sphere with Radial Basis Functions: Error Analysis

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Abstract

Radial basis functions are used to define approximate solutions to boundary integral equations on the unit sphere. These equations arise from the integral reformulation of the Laplace equation in the exterior of the sphere, with given Dirichlet or Neumann data, and a vanishing condition at infinity. Error estimates are proved. Numerical results supporting the theoretical results are presented.

1 Introduction

Throughout this paper we denote by $S$ the unit sphere in $\mathbb{R}^3$, i.e., $S := \{x \in \mathbb{R}^3 : \|x\| = 1\}$, and by $B_e$ the exterior of the sphere, i.e., $B_e := \{x \in \mathbb{R}^3 : \|x\| > 1\}$, where $\|x\|$ denotes the Euclidean norm in $\mathbb{R}^3$. We consider the Laplace equation

$$\Delta U = 0 \quad \text{in } B_e,$$

with either a Dirichlet boundary condition

$$U = U_D \quad \text{on } S,$$

or else a Neumann boundary condition

$$\partial_\nu U = Z_N \quad \text{on } S,$$

where $\partial_\nu = \partial / \partial \nu$ denotes differentiation in the direction of the outward unit normal $\nu$, and the vanishing condition at infinity for both the Dirichlet and Neumann cases is

$$U(x) = O(1/\|x\|) \quad \text{as } \|x\| \to \infty.$$

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The solutions of these problems can be represented in terms of spherical harmonics. A spherical harmonic of order \(l\) on \(S\) is the restriction to \(S\) of a homogeneous harmonic polynomial of degree \(l\) in \(\mathbb{R}^3\). The space of all spherical harmonics of order \(l\) is the eigenspace of the Laplace-Beltrami operator \(\Delta_S\) corresponding to the eigenvalue \(\lambda_l = -l(l+1)\). The dimension of this space being \(2l + 1\) (see e.g. [7, page 4]), one may choose for it an orthonormal basis \(\{Y_{l,m}\}_{m=-l}^{l}\). The collection of all the spherical harmonics \(Y_{l,m}\), \(m = -l, \ldots, l\) and \(l = 0, 1, \ldots\), forms an orthonormal basis for \(L^2(S)\).

Let \((r, \theta, \varphi)\) be the spherical coordinates of a point \(x = (x_1, x_2, x_3) \in \mathbb{R}^3\), where \(r = \|x\|\), and \(\theta\) and \(\varphi\) are the polar and azimuthal angles, so that

\[
x_1 = r \sin \theta \cos \varphi, \quad x_2 = r \sin \theta \sin \varphi, \quad x_3 = r \cos \theta.
\]

For any function \(v \in L^2(S)\), its associated Fourier series,

\[
v = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \hat{v}_{l,m} Y_{l,m}(\theta, \varphi), \quad \text{where} \quad \hat{v}_{l,m} = \int_S v(\theta, \varphi) Y_{l,m}(\theta, \varphi) d\sigma,
\]

converges in \(L^2(S)\). Here \(d\sigma\) is the element of surface area. For more details on spherical harmonics, the reader is referred to Müller’s book [7].

It is well-known that if the Dirichlet data \(U_D\) has an expansion as a sum of spherical harmonics

\[
U_D(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} (U_D)_{l,m} Y_{l,m}(\theta, \varphi),
\]

then (see [9, Theorem 2.5.1]) the Dirichlet problem (1.1), (1.2) and (1.4) has the unique solution

\[
U(r, \theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{1}{r^{l+1}} (U_D)_{l,m} Y_{l,m}(\theta, \varphi). \quad (1.6)
\]

Similarly, if

\[
Z_N(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} (Z_N)_{l,m} Y_{l,m}(\theta, \varphi),
\]

then (see [9, Theorem 2.5.2]) the Neumann problem (1.1), (1.3) and (1.4) has the unique solution

\[
U(r, \theta, \varphi) = -\sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{1}{(l+1)r^{l+1}} (Z_N)_{l,m} Y_{l,m}(\theta, \varphi). \quad (1.7)
\]

The spherical harmonic basis functions in (1.6), (1.7) are global. In contrast, in this paper we intend to use spherical basis functions obtained from compactly supported radial basis functions, which are better able to capture local properties of the solutions. Our intent is to consider the above boundary value problems as
prototypes for more complicated problems for which explicit solutions may not be available. We shall propose a solution process in which the boundary value problems are reformulated in terms of boundary integral equations on \( S \), the solutions of which are then approximated by spherical basis functions.

In the next section we introduce the integral reformulation of the boundary value problems (1.1)–(1.4) into boundary integral equations. Section 3 discusses the use of radial basis functions to define the finite dimensional subspace used in the approximation. The key result of the paper (Theorem 3.7) presents the approximation property in different Sobolev norms (including non-integral and negative norms) of this subspace. This result is employed in Section 4 to prove the convergence of the approximation schemes. Numerical experiments are presented in Section 5 which support the theoretical results.

2 Boundary integral equations and weak formulations

The single-layer potential \( J \) and the double-layer potential \( D \) are defined by

\[
J v(x) = \frac{1}{4\pi} \int_S v(y) \frac{1}{\|x - y\|^2} d\sigma_y \quad \text{and} \quad D v(x) = \frac{1}{4\pi} \int_S v(y) \frac{\partial}{\partial \nu_y} \frac{1}{\|x - y\|^2} d\sigma_y,
\]

for \( x \in \mathbb{R}^3 \). Associated with these potentials, we define the following boundary integral operators

\[
S v(x) = \frac{1}{4\pi} \int_S v(y) \frac{1}{\|x - y\|^2} d\sigma_y,
\]

\[
D v(x) = \frac{1}{4\pi} \int_S v(y) \frac{\partial}{\partial \nu_y} \frac{1}{\|x - y\|^2} d\sigma_y,
\]

\[
D^* v(x) = \frac{1}{4\pi} \frac{\partial}{\partial \nu_x} \int_S v(y) \frac{1}{\|x - y\|^2} d\sigma_y,
\]

\[
N v(x) = \frac{1}{4\pi} \frac{\partial}{\partial \nu_x} \int_S v(y) \frac{\partial}{\partial \nu_y} \frac{1}{\|x - y\|^2} d\sigma_y,
\]

for \( x \in S \). It is well-known that for all \( s \in \mathbb{R} \), the mappings

\[
S : H^{s+1/2}(S) \to H^{s+1/2}(S), \quad N : H^{s+1/2}(S) \to H^{s-1/2}(S),
\]

\[
D : H^{s+1/2}(S) \to H^{s+1/2}(S), \quad D^* : H^{s-1/2}(S) \to H^{s-1/2}(S)
\]

are bounded operators. (If we replace \( S \) by \( \Gamma \), the boundary of a Lipschitz domain in \( \mathbb{R}^3 \), then the above operators are bounded when \( s \in (-1/2, 1/2) \).) The traces and normal derivatives on \( S \) of \( J \) and \( D \) are given by (see e.g. [4, 9], noting that the limits are taken from the exterior of \( S \))

\[
(J v)|_S = S v \quad \text{and} \quad \partial_v(J v) = -\frac{1}{2} v + D^* v, \quad \text{if} \ v \in H^{-1/2}(S),
\]
and
\[(Dv)|_{S} = \frac{1}{2}v + Dv \quad \text{and} \quad \partial_{v}(Dv) = Nv \quad \text{if} \quad v \in H^{1/2}(S).\]

If \(U \in H_{loc}^{1}(\mathbb{E})\) satisfies (1.1) and (1.4), then using the single-layer and double-layer potentials, and Green’s theorem we can represent \(U\) as (see [6, Theorems 7.12 & 8.9])
\[U = D(U|_{S}) - \mathcal{J}(\partial_{v}U) \quad \text{in} \quad \mathbb{E}, \quad (2.1)\]
allowing us to compute \(U\) from a knowledge of both \(U|_{S}\) and \(\partial_{v}U\). In fact, by taking the trace on both sides of (2.1) we obtain, after rearranging the equation,
\[S(\partial_{v}U) = -\frac{1}{2}U|_{S} + D(U|_{S}) \quad \text{on} \quad S.\]

Similarly, by taking the normal derivative of both sides of (2.1) we find
\[N(U|_{S}) = \frac{1}{2}\partial_{v}U + D^{*}(\partial_{v}U) \quad \text{on} \quad S.\]

Therefore, the Dirichlet problem (1.1), (1.2) and (1.4) is equivalent to
\[Sz = f \quad \text{on} \quad S, \quad \text{where} \quad f = -\frac{1}{2}U_{D} + DU_{D}, \quad (2.2)\]
and the Neumann problem (1.1), (1.3) and (1.4) is equivalent to
\[Nu = g \quad \text{on} \quad S, \quad \text{where} \quad g = \frac{1}{2}Z_{N} + D^{*}Z_{N}. \quad (2.3)\]

Due to (2.1), the solution \(U\) of the Dirichlet problem can be computed from the solution \(z\) of (2.2) by
\[U = \mathcal{D}U_{D} - \mathcal{J}z,\]
and the solution of the Neumann problem can be computed from the solution \(u\) of (2.3) by
\[U = \mathcal{D}u - \mathcal{J}Z_{N}.\]

Equation (2.2) is a weakly singular integral equation and equation (2.3) is a hypersingular integral equation. In the following we will design efficient algorithms to solve these equations. We note that \(S\) and \(N\) are pseudo-differential operators of order 1 and \(-1\), respectively. They have the following representations in terms of spherical harmonics (see [9, page 122]):
\[Sv = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{1}{2l+1} \tilde{v}_{l,m}Y_{l,m}, \quad (2.4)\]
\[Nv = -\sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{l(l+1)}{2l+1} \tilde{v}_{l,m}Y_{l,m}. \quad (2.5)\]
In the remaining of this section we shall define weak solutions to (2.2) and (2.3). For $s \in \mathbb{R}$, the Sobolev space $H^s(\mathbb{S})$ is defined as usual (see e.g., [9]) with norm and Hermitian product given by

$$
\|v\|_s := \left( \sum_{l=0}^{\infty} \sum_{m=-l}^{l} (l+1)^{2s} |\widehat{v}_{l,m}|^2 \right)^{1/2}
$$

and

$$
\langle v, w \rangle_s := \sum_{l=0}^{\infty} \sum_{m=-l}^{l} (l+1)^{2s} \widehat{v}_{l,m} \overline{w}_{l,m}.
$$

We note that

$$
|\langle v, w \rangle_s| \leq \|v\|_s \|w\|_s \quad \forall v, w \in H^s(\mathbb{S}), \forall s \in \mathbb{R},
$$

and

$$
\|v\|_{s_1} = \sup_{w \in H^{s_2}(\mathbb{S}) \setminus \{0\}} \frac{\langle v, w \rangle_{s_1 + s_2}}{\|w\|_{s_2}} \quad \forall v \in H^{s_1}(\mathbb{S}), \forall s_1, s_2 \in \mathbb{R}.
$$

It is well-known [6, 9] that $S : H^{-1/2}(\mathbb{S}) \to H^{1/2}(\mathbb{S})$ and $N : H^{1/2}(\mathbb{S})/\mathbb{R} \to H^{-1/2}(\mathbb{S})$ are bijective, implying that (or see (2.4) and (2.5)) (2.2) has a unique solution for all $f \in H^{1/2}(\mathbb{S})$, and (2.3) has a unique solution up to a constant for all $g \in H^{-1/2}(\mathbb{S})$. Defining the bilinear forms

$$
a_S(v, w) := \langle Sv, w \rangle_0 \quad \forall v, w \in H^{-1/2}(\mathbb{S})
$$

and

$$
a_N(v, w) := -\langle Nv, w \rangle_0 \quad \forall v, w \in H^{1/2}(\mathbb{S}),
$$

we seek weak solutions to equations (2.2) and (2.3) respectively as follows:

$$
z \in H^{-1/2}(\mathbb{S}) : a_S(z, v) = \langle f, v \rangle_0 \quad \forall v \in H^{-1/2}(\mathbb{S}),
$$

and

$$
u \in H^{1/2}(\mathbb{S}) : \int_{\mathbb{S}} u(x) \, d\sigma_x = 0 \quad \text{and} \quad a_S(u, v) = -\langle g, v \rangle_0 \quad \forall v \in H^{1/2}(\mathbb{S}).
$$

We note from (2.4) and (2.5) that

$$
a_S(v, v) \simeq \|v\|_{-1/2}^2 \quad \forall v \in H^{-1/2}(\mathbb{S}) \quad \text{and} \quad a_N(v, v) \simeq \|v\|_{1/2}^2 \quad \forall v \in H^{1/2}(\mathbb{S})/\mathbb{R}.
$$

In the following we shall approximate the solutions of the above equations by using spherical basis functions. These functions are defined via positive definite kernels.
3 Approximation by spherical basis functions

The finite dimensional subspaces that we shall use in our approximation are defined by positive definite kernels on $S$ and spherical basis functions.

3.1 Positive definite kernels and native spaces

A continuous function $\Phi : S \times S \rightarrow \mathbb{C}$ is called a positive definite kernel on $S$ if it satisfies

(i) $\Phi(x, y) = \overline{\Phi(y, x)}$ for all $x, y \in S$;

(ii) for every set of distinct points $\{x_1, \ldots, x_M\}$ on $S$, the $M \times M$ matrix $A$ with entries $A_{i,j} = \Phi(x_i, x_j)$ is positive semi-definite.

If the matrix $A$ is positive definite then $\Phi$ is called a strictly positive definite kernel; see [12, 16].

We shall define the kernel $\Phi$ in terms of a univariate function $\phi : [-1, 1] \rightarrow \mathbb{R}$,

$$\Phi(x, y) = \phi(x \cdot y) \quad \forall x, y \in S.$$  

If $\phi$ has a series expansion in terms of Legendre polynomials $P_l$,

$$\phi(t) = \frac{1}{4\pi} \sum_{l=0}^{\infty} (2l + 1)\hat{\phi}(l)P_l(t),$$  

where

$$\hat{\phi}(l) = 2\pi \int_{-1}^{1} \phi(t)P_l(t) dt,$$

then due to the addition formula [7, 9]

$$\sum_{m=-l}^{l} Y_{l,m}(x)\overline{Y_{l,m}(y)} = \frac{2l + 1}{4\pi} P_l(x \cdot y) \quad \forall x, y \in S,$$

the kernel $\Phi$ can be represented as

$$\Phi(x, y) = \sum_{l=0}^{\infty} \hat{\phi}(l) \sum_{m=-l}^{l} Y_{l,m}(x)\overline{Y_{l,m}(y)}.$$  

This kernel is called a zonal kernel. In [2], a complete characterisation of strictly positive definite kernels is established: the kernel $\Phi$ is strictly positive definite if and only if $\hat{\phi}(l) \geq 0$ for all $l \geq 0$, and $\hat{\phi}(l) > 0$ for infinitely many even values of $l$ and infinitely many odd values of $l$; see also [12] and [16]. In the following we shall assume that $\hat{\phi}(l) > 0$ for all $l \geq 0$. 

6
The native space associated with $\phi$ is defined by

$$\mathcal{N}_\phi := \{ v \in \mathcal{D}'(S) : \|v\|_\phi^2 = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{\hat{v}_{l,m}^2}{\phi(l)} < \infty \},$$

where $\mathcal{D}'(S)$ is the space of distributions defined on $S$. This space is equipped with an inner product and a norm defined by

$$\langle v, w \rangle_\phi = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{\hat{v}_{l,m} \overline{\hat{w}_{l,m}}}{\phi(l)} \quad \text{and} \quad \|v\|_\phi = \left( \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{\hat{v}_{l,m}^2}{\phi(l)} \right)^{1/2}.$$  

If the coefficients $\hat{\phi}(l)$ for $l = 0, 1, \ldots$ satisfy

$$c_1(l + 1)^{-2\tau} \leq \hat{\phi}(l) \leq c_2(l + 1)^{-2\tau} \quad (3.5)$$

for some positive constants $c_1$ and $c_2$, and some $\tau \in \mathbb{R}$, then the native space $\mathcal{N}_\phi$ can be identified with the Sobolev space $H^s(S)$, and the corresponding norms are equivalent. In particular, if $\tau > 1$ then the series (3.1) converges pointwise and $\mathcal{N}_\phi \subset C(S)$, which is essentially the Sobolev embedding theorem.

### 3.2 Spherical basis functions and approximation properties

Let $X = \{ \mathbf{x}_1, \ldots, \mathbf{x}_M \}$ be a set of data points on the sphere. Two important parameters characterising the set $X$ are the mesh norm $h_X$ and separation radius $q_X$, defined by

$$h_X := \sup_{y \in S} \min_{1 \leq i \leq M} \theta(\mathbf{x}_i, y) \quad \text{and} \quad q_X := \frac{1}{2} \min_{i \neq j} \theta(\mathbf{x}_i, \mathbf{x}_j),$$

where $\theta(\mathbf{x}, y) := \cos^{-1}(\mathbf{x} \cdot y)$. The spherical basis functions $\Phi_i, i = 1, \ldots, M$, associated with $X$ and the kernel $\Phi$ are defined by

$$\Phi_i(\mathbf{x}) := \Phi(\mathbf{x}, \mathbf{x}_i) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \hat{\phi}(l) \overline{Y_{l,m}(\mathbf{x}_i)} Y_{l,m}(\mathbf{x}). \quad (3.6)$$

We note that if (3.5) holds then $\Phi_i \in H^s(S)$ for all $s$ satisfying $s < 2\tau - 1$.

Let

$$V_X^\phi := \text{span}\{\Phi_1, \ldots, \Phi_M\}. \quad (3.7)$$

In the following we will assume that (3.5) holds for some $\tau > 1$ so that $V_X^\phi \subset \mathcal{N}_\phi = H^s(S) \subset C(S)$. We now study the approximation property of $V_X^\phi$ as a subspace of Sobolev spaces. The following lemma shows the boundedness of the interpolation operator in the native space.

7
Lemma 3.1 The interpolation operator $I_X : C(S) \to V^\phi_X$ defined by

$$I_X v(x_j) = v(x_j), \quad j = 1, \ldots, M, \quad v \in C(S),$$  \hspace{1cm} (3.8)

is well-defined, and is a bounded operator in $N^\phi$.

Proof. Finding $I_X v$ satisfying (3.8) entails, on writing $I_X v = \sum_{i=0}^M c_i \Phi_i$, solving the system

$$\sum_{i=1}^M c_i \Phi_i(x_j) = v(x_j), \quad j = 1, \ldots, M.$$  

This has a unique solution due to the positive definiteness of the matrix $(\Phi_i(x_j))_{i,j=1}^M$. Moreover, for any continuous function $v$ there holds

$$\langle v, \Phi_j \rangle_\phi = \sum_{l=0}^\infty \sum_{m=-l}^l \frac{\hat{u}_{l,m} \hat{\phi}(l) Y_{l,m}(x_j)}{\hat{\phi}(l)} = v(x_j),$$

so that (3.8) is equivalent to

$$\langle I_X v, \Phi_j \rangle_\phi = \langle v, \Phi_j \rangle_\phi, \quad j = 1, \ldots, M.$$  

Hence

$$\|I_X v - v\|_\phi^2 = \langle I_X v - v, I_X v - v \rangle_\phi = \langle I_X v - v, -v \rangle_\phi \leq \|I_X v - v\|_\phi \|v\|_\phi,$$

implying

$$\|I_X v - v\|_\phi \leq \|v\|_\phi \quad \forall v \in N^\phi.$$  \hspace{1cm} (3.9)

This proves that $I_X$ is a bounded operator in $N^\phi$. \hfill \Box

The following proposition is a consequence of a non-trivial result proved in [5].

Proposition 3.2 For any $\sigma > 1$, if $w \in H^\sigma(S)$ satisfies $w|_X = 0$ for some set $X := \{x_1, \ldots, x_M\} \subset S$ then the following estimate holds

$$\|w\|_t \leq c h^{-t}_X \|w\|_\sigma, \quad 0 \leq t \leq \sigma,$$

where $c$ may depend on $t$.

Proof. It is proved in [5, Theorem 3.3] that $w|_X = 0$ implies

$$\|w\|_0 \leq c h^{-1}_X \|w\|_\sigma.$$  

This inequality together with $\|w\|_\sigma \leq \|w\|_\sigma$ and a standard interpolation argument yields the required estimate. (For this interpolation argument, the reader is referred to e.g. [1, 4, 6]. A simple proof for the case of Sobolev spaces on the sphere can be found in [3].) \hfill \Box

A direct consequence of the above proposition and (3.9) is the following error estimate when $v \in H^\tau(S)$ is approximated by its interpolant $I_X v$. 

8
Corollary 3.3 Assume that (3.5) holds for some $\tau > 1$. If $v \in H^\tau(S)$ then for any $t \in [0, \tau]$ there holds
\[ \|I_Xv - v\|_t \leq ch_X^{\tau-t}\|v\|_\tau. \]

Proof. This is a result of Proposition 3.2 (taking $w = I_Xv - v$), of (3.9) and the equivalence of the native space norm and $H^\tau$-norm. \qed

When $v$ is smoother, the error bound can be improved using the technique developed in [11] and [15], which is modified in [13] for hybrid approximation using radial basis functions and polynomials. The crucial tool is the isomorphism defined in the following lemma.

Lemma 3.4 Assume that (3.5) holds for some $\tau > 0$. For $s \in \mathbb{R}$, let $T : H^{s-\tau}(S) \to H^{s+\tau}(S)$ be defined by
\[ T\psi := \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \hat{\phi}(l)\hat{\psi}_{l,m}Y_{l,m}. \]

Then
\[ (i) \ T \ is \ an \ isomorphism \ satisfying \]
\[ \|T\psi\|_{s+\tau} \simeq \|\psi\|_{s-\tau} \ \forall \psi \in H^{s-\tau}(S); \]  
\[ (3.10) \]

\[ (ii) \ For \ any \ \psi \in H^{-\tau}(S) \ and \ \xi \in \mathcal{N}_{\phi} \ there \ holds \]
\[ \langle T\psi, \xi \rangle_\phi = \langle \psi, \xi \rangle_0, \]  
\[ (3.11) \]
i.e., $T$ is the adjoint of the embedding operator of the native space $\mathcal{N}_\phi$ into $H^0(S)$.

Proof. It is clear that, under the assumption (3.5), $T$ is well-defined for all $\psi \in H^{s-\tau}(S)$, and has an inverse given by
\[ T^{-1}\eta = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \hat{\eta}_{l,m}Y_{l,m}. \]

Properties (3.10)–(3.11) follow from (3.5), the definitions of various inner products and Sobolev norms, noting that $(T\psi)_{l,m} = \hat{\phi}(l)\hat{\psi}_{l,m}$. \qed

With the help of the above lemma, the error bound for the interpolation can be improved.

Proposition 3.5 Assume that (3.5) holds for some $\tau > 1$. For any $s, t \in \mathbb{R}$ satisfying $0 \leq t \leq \tau \leq s \leq 2\tau$, if $v \in H^{s}(S)$ then the following estimate holds
\[ \|I_Xv - v\|_t \leq C h_X^{\min\{s-\tau, 2(\tau-t)\}}\|v\|_s. \]
Proof. Consider first the case when \( v \in H^{2\tau}(\mathbb{S}) \). By Lemma 3.4, we can write \( v = T\psi \) for some \( \psi \in H^0(\mathbb{S}) \). It follows from Proposition 3.2 and the equivalence of the \( H^\tau \)-norm and \( \| \cdot \|_\phi \)-norm that

\[
\| I_X v - v \|_0^2 \leq c h_X^{2\tau} \| I_X v - v \|_\phi^2 = c h_X^{2\tau} \langle I_X v - v, I_X v - v \rangle_\phi.
\]

Using the orthogonality property of the projection \( I_X \) we have

\[
\langle I_X v - v, I_X v - v \rangle_\phi = \langle v - I_X v, v \rangle_\phi,
\]

and therefore, with the help of (3.10) and (3.11) (taking \( s = \tau \)),

\[
\| I_X v - v \|_0^2 \leq c h_X^{2\tau} \langle v - I_X v, T\psi \rangle_\phi \leq c h_X^{2\tau} \langle v - I_X v, \psi \rangle_0 \\
\leq c h_X^{2\tau} \| I_X v - v \|_0 \| \psi \|_0 \leq c h_X^{2\tau} \| I_X v - v \|_0 \| v \|_{2\tau},
\]

implying

\[
\| I_X v - v \|_0 \leq c h_X^{2\tau} \| v \|_{2\tau}. \tag{3.12}
\]

Now assume that \( v \in H^s(\mathbb{S}) \), \( \tau \leq s \leq 2\tau \). We can write \( s \) as

\[
s = (1 - \theta)\tau + 2\theta\tau \tag{3.13}
\]

for some \( \theta \in [0, 1] \). More precisely, \( \theta = (s - \tau)/\tau \). If \( 0 \leq t \leq 2\tau - s \) we define \( t' = t/(1 - \theta) \) to have

\[
0 \leq t' \leq \tau \quad \text{and} \quad t = (1 - \theta)t' + 0 \times \theta. \tag{3.14}
\]

Corollary 3.3 gives

\[
\| I_X v - v \|_t \leq c h_X^{2\tau-t} \| v \|_t.
\]

By using interpolation, we deduce from the above estimate and (3.12), noting (3.13) and (3.14),

\[
\| I_X v - v \|_t \leq c \left( h_X^{2\tau} \right)^\theta \left( h_X^{\tau-t} \right)^{1-\theta} \| v \|_s = c h_X^{\tau+\theta\tau-t} \| v \|_s \\
= c h_X^{s-t} \| v \|_s. \tag{3.15}
\]

We note that \( s - t \leq 2(\tau - t) \) for \( t \in [0, 2\tau - s] \).

If \( 2\tau - s < t \leq \tau \), we write

\[
t = (1 - \theta')\tau + \theta'(2\tau - s),
\]

where \( \theta' = (\tau - t)/(s - \tau) \). By interpolation there holds

\[
\| I_X v - v \|_t \leq \| I_X v - v \|_{2\tau-s} \| I_X v - v \|_{1-\theta'}^{\frac{\theta'}{\tau - s}}. \]
It follows from Corollary 3.3, noting \( \|v\|_\tau \leq \|v\|_s \), that
\[
\|I_X v - v\|_\tau \leq c\|v\|_s.
\]
Therefore, with the help of (3.15) (with \( t = 2\tau - s \)) we infer
\[
\|I_X v - v\|_t \leq ch_X^{2(\tau-t)}\|v\|_s = ch_X^{2(\tau-t)}\|v\|_s.
\]
We finish the proof by noting that \( 2(\tau-t) < s - t \) for \( 2\tau - s < t \leq \tau \). \[\square\]

**Remark 3.6** We note that the estimate proved in the above proposition is only optimal when \( 0 \leq t \leq 2\tau - s \) and \( \tau \leq s \leq 2\tau \).

The convergence analysis for the approximate solutions to (2.9) and (2.10) requires the approximation property of \( V^\phi_X \) in a larger range of Sobolev norms than those considered in the above proposition, namely error bounds are sought when the approximated function \( v \) belongs to \( H^s(S) \) for \( s < \tau \) (e.g. \( s = 1/2 \) in the case of (2.10) and \( s = -1/2 \) in the case of (2.9)). The following theorem states our most general approximation result for \( V^\phi_X \).

**Theorem 3.7** Assume that (3.5) holds for some \( \tau > 1 \). For any \( s, t \in \mathbb{R} \) satisfying \( t \leq \tau, -2\tau \leq s \leq 2\tau \), and \( t \leq s \), if \( v \in H^s(S) \) then there exists \( \eta \in V^\phi_X \) such that
\[
\|v - \eta\|_t \leq C h_X^{\mu}\|v\|_s, \tag{3.16}
\]
where \( \mu = \min\{s - t, 2(\tau - t), 2\tau + |s|\} \), and where the constant \( C \) is independent of \( v \) and \( h_X \).

**Proof.** We prove the result by considering different cases of values of \( s \) and \( t \).

**Case 1:** \( 0 \leq t \leq \tau \leq s \leq 2\tau \)

We note that in this case \( \mu = \min\{s - t, 2(\tau - t)\} \), and the result is in fact Proposition 3.5.

In the following cases, it is easy to see that \( s - t \leq 2(\tau - t) \) and thus \( \mu = \min\{s - t, 2\tau + |s|\} \).

**Case 2:** \( 0 \leq t \leq s < \tau \)

Let \( L = \lfloor \frac{1}{h_X} \rfloor \). We define for each \( v \in H^s(S) \) a polynomial of degree \( L \) by
\[
P_L v = \sum_{l=0}^L \sum_{m=-l}^l \tilde{\varphi}_{l,m} Y_{l,m}.
\]
With \( \eta = I_X P_L v \) we have
\[
\|v - \eta\|_t^2 \leq 2\|v - P_L v\|_t^2 + 2\|P_L v - I_X P_L v\|_t^2
\]
\[
\leq 2 \sum_{l=L+1}^{\infty} \sum_{m=-l}^{l} (l + 1)^2|\widehat{\eta}_{l,m}|^2 + ch_X^{2(t-t)}\|P_L v\|_r^2
\]
\[
= 2 \sum_{l=L+1}^{\infty} \sum_{m=-l}^{l} (l + 1)^2(l + 1)^2|\widehat{\eta}_{l,m}|^2
\]
\[
+ ch_X^{2(t-t)} \sum_{l=1}^{L} \sum_{m=-l}^{l} (l + 1)^2(l + 1)^2|\widehat{\eta}_{l,m}|^2
\]
\[
\leq c(L + 1)^2|\|v\|_s|^2 + cL^{2(t-t)}h_X^{2(t-t)}\|v\|_s^2,
\]
where in the second step we have used the result given in Case 1. Since \( L \leq h_X^{-1} \) and \( (L + 1)^{-1} \leq h_X \), we deduce (3.16) with \( \mu = s - t \).

**Case 3:** \( t < 0 \leq s \leq 2\tau \)

Let \( P_0 : H^0(S) \to V_X^\phi \) be the projection defined by
\[
P_0 v \in V_X^\phi : \quad \langle P_0 v, w \rangle_0 = \langle v, w \rangle_0 \quad \forall w \in V_X^\phi.
\]
Then \( P_0 v \) is the best approximation of \( v \) from \( V_X^\phi \) in the \( H^0 \)-norm, thus the results proved in Cases 1 and 2 give
\[
\|P_0 v - v\|_0 \leq ch_X^s\|v\|_\sigma \quad \forall v \in H^\sigma(S), \ 0 \leq \sigma \leq 2\tau.
\]

If \(-2\tau \leq t < 0\) we have
\[
\|P_0 v - v\|_t = \sup_{w \in H^{-t}(S)} \frac{\langle v - P_0 v, w \rangle_0}{\|w\|_{-t}} = \sup_{w \in H^{-t}(S)} \frac{\langle v - P_0 v, w - P_0 w \rangle_0}{\|w\|_{-t}}
\]
\[
\leq \|v - P_0 v\|_0 \sup_{w \in H^{-t}(S)} \frac{\|w - P_0 w\|}_0 \|w\|_{-t}
\]
\[
\leq ch_X^s\|v\|_s h_X^{-1}.
\]

If \( t < -2\tau \) then
\[
\|P_0 v - v\|_t \leq \|P_0 v - v\|_{-2\tau} \leq ch_X^{2\tau+s}\|v\|_s.
\]

**Case 4:** \(-2\tau \leq s < 0\) and \( t \leq s\)

Let \( P_s : H^s(S) \to V_X^\phi \) be defined by
\[
\langle P_s v, w \rangle_s = \langle v, w \rangle_s \quad \forall w \in V_X^\phi.
\]
It is easily seen that
\[
\|P_s v - v\|_s \leq \|v\|_s.
\]
If \(2(s - \tau) \leq t \leq 2s\) so that \(0 \leq 2s - t \leq 2\tau\) then for any \(w \in H^{2s-t}(S)\) the result proved in Case 3 ensures the existence of \(\eta_w \in V^\phi_X\) satisfying
\[
\|w - \eta_w\|_s \leq ch_X^{s-t}\|w\|_{2s-t}.
\]
Using (2.7) and (2.8) we then deduce
\[
\|P_s v - v\|_t = \sup_{w \in H^{2s-t}(S)} \frac{\langle P_s v - v, w \rangle_s}{\|w\|_{2s-t}} = \sup_{w \in H^{2s-t}(S)} \frac{\langle P_s v - v, w - \eta_w \rangle_s}{\|w\|_{2s-t}} 
\leq ch_X^{s-t}\|P_s v - v\|_s \leq ch_X^{s-t}\|v\|_s.
\]
In particular, we have
\[
\|P_s v - v\|_{2s} \leq ch_X^{-s}\|v\|_s.
\]
The result for \(2s < t \leq s\) is obtained by interpolation, noting (3.17).

If \(t < 2(s - \tau)\) then
\[
\|P_s v - v\|_t \leq \|P_s v - v\|_{2(s - \tau)} \leq ch_X^{2s-t}\|v\|_s.
\]
The theorem is proved. \(\square\)

The next section details how approximate solutions to (2.9) and (2.10) are sought in finite dimensional spaces of the type defined in this section.

## 4 Galerkin approximations

The finite dimensional space \(V^\phi_X\) defined in (3.7) depends on the univariate function \(\phi\). In this section we shall choose appropriate functions \(\phi\) for each of the two equations (2.9) and (2.10).

### 4.1 The hypersingular integral equation

For the approximation of (2.10) we use radial basis functions suggested by Wendland [14, page 128]. First we define a smoothing operator \(I\) on the space \(C_K[0, \infty)\) of continuous functions in \([0, \infty)\) with compact supports by
\[
I : C_K[0, \infty) \to C_K[0, \infty), \quad Iv(r) = \int_r^\infty sv(s) \, ds, \quad r \geq 0.
\]
For any non-negative integer \(m\), let
\[
\tilde{\rho}_m(r) = \begin{cases} (1 - r)^{m+2}, & 0 < r \leq 1, \\ 0, & r > 1, \end{cases}
\]
and
\[
\rho_m(r) = I^m \tilde{\rho}_m(r), \quad r \geq 0.
\]
We define
\[ N(t) = m(\sqrt{2} - 2t), \quad t \in [-1, 1], \] (4.1)
and denote by \( \Phi_i^N, \ i = 1, \ldots, M, \) the corresponding spherical basis functions; see (3.6). These functions are locally supported radial basis functions. Strict positive definiteness is proved in [15, Theorem 9.13]. It is proved in [8, Proposition 4.6] that \( \hat{\phi}_N(l) \) satisfies (3.5) with
\[ \tau_N = m + 3/2. \] (4.2)

In Figure 1 we plotted \( \hat{\phi}_N(l)/l^{2m+3} \) to observe the asymptotic behaviour of \( \hat{\phi}_N(l) \) for \( m = 0, 1, 2, 3 \), with \( \hat{\phi}_N(l) \) computed by the MATLAB function \text{quadl} which uses an adaptive Lobatto quadrature. Effects of integration errors are seen for \( l \) in the hundreds and \( m = 2, 3 \).

![Figure 1: Asymptotic behaviour of \( \hat{\phi}_N(l) \), degree = \( l \), ratio = \( \hat{\phi}_N(l)/l^{2m+3} \)](image)

For given \( X = \{x_1, \ldots, x_M\} \subset S \), let \( V_N := V_X^{\hat{\phi}_N} \). We will solve (2.10) approximately by solving instead
\[ u_X \in V_N : \quad \int_S u_X(x) \, d\sigma_x = 0 \quad \text{and} \quad a_N(u_X, v_X) = -\langle g, v_X \rangle_0 \quad \forall v_X \in V_N. \] (4.3)
The conformity condition $V_N \subset H^{1/2}(S)$ requires $\tau_N > 3/4$, and the approximation property (Theorem 3.7) requires $\tau_N > 1$. Both conditions hold for $m = 0, 1, 2, \ldots$.

By using (2.5) and (3.3), we obtain the following formula to compute the entries of the stiffness matrix resulting from equation (4.3):

$$a_N(\Phi_i^N, \Phi_j^N) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{l(l+1)}{2l+1} |\hat{\phi}_N(l)|^2 Y_{l,m}(x_i) Y_{l,m}(x_j)$$

$$= \frac{1}{4\pi} \sum_{l=0}^{\infty} (l+1) |\phi_N(l)|^2 P_{l}(x_i \cdot x_j). \quad (4.4)$$

The right-hand side in (4.3) is computed by using (2.3), noting $D^* = -S/2$ (see [9, page 122]), as follows:

$$\langle g, \Phi_i^N \rangle_0 = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \left( \frac{1}{2} - \frac{1}{2(2l+1)} \right) \hat{(Z_N)}_{l,m}(x_i) \hat{\phi}_N(l) Y_{l,m}(x_i)$$

$$= \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{l}{2l+1} \hat{(Z_N)}_{l,m}(x_i) \hat{\phi}_N(l) Y_{l,m}(x_i). \quad (4.5)$$

Theorem 3.7 yields the following a priori error estimate.

**Theorem 4.1** Let $\phi_N$ be defined by (4.1) for some non-negative integer $m$, and let $\tau_N = m + 3/2$. If $u$ is the solution to (2.10) satisfying $u \in H^s(S)$, $1/2 \leq s \leq 2\tau_N$, and $u_X$ the solution to (4.3) then

$$\|u - u_X\|_{1/2} \leq C h_X^{\min\{s-1/2, 2\tau - 1\}} \|u\|_s.$$

**Proof.** The condition

$$\int_S u(x) \, d\sigma_x = \int_S u_X(x) \, d\sigma_x = 0$$

yields $\tilde{u}_{0,0} = (u_X)_{0,0} = 0$, implying (together with (2.11))

$$\|u - u_X\|_{1/2}^2 \simeq a_N(u - u_X, u - u_X) = a_N(u - u_X, u - w_X) \leq c \|u - u_X\|_{1/2} \|u - w_X\|_{1/2}$$

for all $w_X \in V_N$. This implies

$$\|u - u_X\|_{1/2} \leq c \inf_{w_X \in V_N} \|u - w_X\|_{1/2},$$

and the required estimate is now a consequence of Theorem 3.7. \qed
4.2 The weakly singular integral equation

The same family of univariate functions defined in (4.1) can be used to define the finite dimensional subspace in the approximation of (2.9). However, for the purpose of preconditioning to be studied in a future paper, we choose to relate \( S \) to \( N \) by (cf. (3.1))

\[
S(t) = \frac{1}{4\pi} \sum_{l=0}^{\infty} (2l+1)(l+1)\hat{\phi}_N(l)P_l(t),
\]

and denote by \( \Phi_i^S, i = 1, \ldots, M \), the corresponding spherical basis functions. It is clear that \( \hat{\phi}_S(l) \) satisfies (3.5) with \( \tau_S = \tau_N - 1/2 = m + 1 \);

see (4.2).

Letting

\[
V_S := V_X^{\phi_S} = \text{span}\{\Phi_1^S, \ldots, \Phi_M^S\},
\]

we approximate the solution \( u \) of (2.9) by

\[
z_X \in V_S: \quad a_S(z_X, v_X) = \langle f, v_X \rangle \quad \forall v_X \in V_S.
\]

The resulting stiffness matrix has entries given as (cf. (4.4))

\[
a_S(\Phi_i^S, \Phi_j^S) = \sum_{l=0}^{\infty} \frac{(l+1)^2}{2l+1} \left| \hat{\phi}_N(l) \right|^2 \sum_{m=-l}^{l} \overline{Y_{l,m}(x_i)}Y_{l,m}(x_j)
\]

\[
= \frac{1}{4\pi} \sum_{l=0}^{\infty} (l+1)^2 \left| \hat{\phi}_N(l) \right|^2 P_l(x_i \cdot x_j).
\]

The right-hand side of (4.7) is computed by using (2.2), noting \( D = -S/2 \) (see [9, page 122]),

\[
\langle f, \Phi_i^S \rangle = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \left( -\frac{1}{2} - \frac{1}{2(2l+1)} \right) (l+1)\overline{(U_D)_{l,m}\hat{\phi}_N(l)Y_{l,m}(x_i)}
\]

\[
= -\sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{(l+1)^2}{2l+1} \overline{(U_D)_{l,m}\hat{\phi}_N(l)Y_{l,m}(x_i)}.
\]

\[
\text{(4.8)}
\]

A priori error estimates similarly to those in Theorem 4.1 can be proved.

**Theorem 4.2** Let \( \phi_N \) be defined by (4.1) for some positive integer \( m \), and let \( \tau_S = m + 1 \). If \( z \) is the solution to (2.9) satisfying \( z \in H^s(S) \), \(-1/2 \leq s \leq 2\tau_S \), and \( z_X \) the solution to (4.7), then

\[
\|z - z_X\|_{-1/2} \leq C h_X^{s+1/2}\|z\|_s.
\]

**Proof.** We note that approximation property requires \( m > 0 \). Since

\[
\|z - z_X\|_{-1/2} \simeq a_S(z - z_X, z - z_X),
\]

the proof is similar to that of Theorem 4.1 and is therefore omitted. \( \square \)
5 Numerical experiments

In this section, we present numerical results obtained from experiments with the set of scattered points $X$ generated by a simple algorithm [10] which partitions the sphere into equal areas; see Figure 2. We chose the sets of points carefully so that the mesh norms $h_X$ of different sets are reasonably different in order to easily observe the order of convergence. The sets of points we used have number of points $M = 20, 30, 40, 50, 100, 500, \text{ and } 1000$. Note that these experiments are purely for observing the order of convergence. In a following paper, we will experiment with sets of real data points obtained by satellites.

5.1 The Neumann problem

We solved the exterior Neumann problem (1.1), (1.3) and (1.4) with a boundary data given by

$$Z_N(x) = \frac{0.5x_3 - 1}{(1.25 - x_3)^{3/2}},$$
so that the exact solution is

\[ U(x) = \frac{1}{\|x - p\|} \quad \text{with} \quad p = (0, 0, 0.5). \]

Here \( x = (x_1, x_2, x_3) \). An approximation to (2.10) will be sought and compared to the exact solution which, due to (2.1) and (2.3), is given by \( u = U|_S \).

The spherical basis functions \( \Phi_i^N, \ i = 1, \ldots, M \), are defined by (3.6) using the univariate function \( \phi_N \) given by (4.1) with \( m = 0, 1, 2 \). The coefficients \( \hat{\phi}_N(l), \ l = 1, \ldots, 500 \), are computed by the MATLAB function \texttt{quadl} which uses an adaptive Lobatto quadrature. The errors are approximated by

\[
\|u_X - u\|_{1/2} \approx \left( \sum_{l=1}^{500} \sum_{m=-l}^{l} (l + 1) |(u_X)_{l,m} - \hat{u}_{l,m}|^2 \right)^{1/2}.
\]

By using the identity (see e.g. [9, page 20])

\[(1 - 2r \cos \theta + r^2)^{-1/2} = \sum_{l=0}^{\infty} r^l P_l(\cos \theta), \quad r < 1,\]

we can easily obtain

\[ \hat{u}_{l,m} = \frac{1}{2^l} Y_l,m(n), \quad n = (0, 0, 1). \]

On the other hand,

\[ (u_X)_{l,m} = \hat{\phi}_N(l) \sum_{i=1}^{M} c_i Y_l,m(x_i). \]

Due to the addition formula (3.3), there holds

\[
\sum_{m=-l}^{l} (l + 1) |(u_X)_{l,m} - \hat{u}_{l,m}|^2 = \frac{(l + 1)(2l + 1)}{4\pi} \left( (\hat{\phi}_N(l))^2 \sum_{i,j=1}^{M} c_i c_j P_l(x_i \cdot x_j) \right.
\]

\[ - \frac{\hat{\phi}_N(l)}{2^{l-1}} \sum_{i=1}^{M} c_i P_l(x_i \cdot n) + \frac{1}{2^{2l}} \right).\]

It is expected from our theoretical result (Theorem 4.1) that the order of convergence for the \( H^{1/2} \)-norm of the error is \( 2(m + 1) \). The estimated orders of convergence (EOC) shown in Tables 1–3 appear to agree with our theoretical results, even though the orders seem to drop for large values of \( M \) when \( m = 2 \).
5.2 The Dirichlet problem

We also solved the exterior Dirichlet problem (1.1), (1.2) and (1.4) with boundary data

\[ U_D(x) = \frac{1}{(1.25 - x_3)^{1/2}}. \]

The exact solution is given by

\[ U(x) = \frac{1}{\|x - p\|} \quad \text{with} \quad p = (0, 0, 0.5), \]

and hence, due to (2.1) and (2.2), the approximate solution to (2.9) is compared to

\[ z(x) = \partial_r U(x) = -\frac{1 + x \cdot p}{\|x - p\|^3} = \frac{(0.5x_3 - 1)}{(1.25 - x_3)^{3/2}}. \]

The spherical basis functions \( \Phi_i^S, \ i = 1, \ldots, M, \) are defined by (3.6) with \( \Phi_S \) given by (4.6) where \( \phi_N \) is defined as in Subsection 5.1. The errors are approximated by

\[ \|z_X - z\|_{-1/2} \approx \left( \sum_{l=1}^{500} \sum_{m=-l}^{l} \frac{|(z_X)_{l,m} - \hat{z}_{l,m}|^2}{l + 1} \right)^{1/2}. \]

The coefficients in the spherical harmonics expansion of the exact solution \( z \) are

\[ \hat{z}_{l,m} = -\frac{l + 1}{2^l} Y_{l,m}(n), \]

and of the approximate solution \( z_X \) are

\[ (\hat{z}_X)_{l,m} = (l + 1) \phi_N(l) \sum_{i=1}^{M} c_i Y_{l,m}(x_i). \]

The addition formula yields

\[
\sum_{m=-l}^{l} \frac{|(z_X)_{l,m} - \hat{z}_{l,m}|^2}{l + 1} = (l + 1)(2l + 1) \left( \frac{(\phi_N(l))^2}{4\pi} \sum_{i,j=1}^{M} c_i c_j P_i(x_i \cdot x_j) \right) + \frac{\phi_N(l)}{2^{2l - 1}} \sum_{i=1}^{M} c_i P_i(x_i \cdot n) + \frac{1}{2^{2l}}.
\]

Our theoretical result (Theorem 4.2) requires \( m > 0 \) and an order of convergence of \( 2m + 5/2 \) is shown in the \( H^{-1/2} \)-norm. We carried out the experiment for \( m = 0, 1, 2 \), and observed some agreement between the estimated orders of convergence and our theoretical result (Tables 4–6). The case when \( m = 0 \) is the borderline case; the theory holds for all positive real values of \( m \).
Acknowledgement

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References


### Table 1: Errors in the $H^{1/2}$-norm with $m = 0$

<table>
<thead>
<tr>
<th>$M$</th>
<th>$h_X$</th>
<th>$|u_X - u|_{1/2}$</th>
<th>EOC</th>
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<td>0.6514</td>
<td>0.608725</td>
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### Table 2: Errors in the $H^{1/2}$-norm with $m = 1$

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<th>$|u_X - u|_{1/2}$</th>
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### Table 3: Errors in the $H^{1/2}$-norm with $m = 2$

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Table 4: Errors in the $H^{-1/2}$-norm with $m = 0$

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<td>0.05752374</td>
<td>2.4712</td>
</tr>
<tr>
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<td>0.1237</td>
<td>0.00738520</td>
<td>2.6654</td>
</tr>
<tr>
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<td>0.0849</td>
<td>0.00303676</td>
<td>2.3611</td>
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</table>

Table 5: Errors in the $H^{-1/2}$-norm with $m = 1$

<table>
<thead>
<tr>
<th>M</th>
<th>$h_X$</th>
<th>$|u_X - u|_{-1/2}$</th>
<th>EOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.6514</td>
<td>0.93557363</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.4418</td>
<td>0.18160356</td>
<td>4.2222</td>
</tr>
<tr>
<td>50</td>
<td>0.3750</td>
<td>0.07737696</td>
<td>5.2042</td>
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<tr>
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<td>0.02040514</td>
<td>3.9327</td>
</tr>
<tr>
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<td>0.1237</td>
<td>0.00044995</td>
<td>4.9529</td>
</tr>
<tr>
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<td>0.0849</td>
<td>0.00011319</td>
<td>3.6667</td>
</tr>
</tbody>
</table>

Table 6: Errors in the $H^{-1/2}$-norm with $m = 2$

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<th>$h_X$</th>
<th>$|u_X - u|_{-1/2}$</th>
<th>EOC</th>
</tr>
</thead>
<tbody>
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<td>0.34892603</td>
<td>4.9632</td>
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<td>0.13191711</td>
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<td>5.0261</td>
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<td>0.00012735</td>
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<tr>
<td>1000</td>
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<td>0.00005865</td>
<td>2.0600</td>
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</tbody>
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