Fast iterative solvers for boundary value problems on a local spherical region

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Abstract

Boundary value problems on local spherical regions arise naturally in geophysics and oceanography when scientists model a physical quantity on large scales. Meshless methods using radial basis functions (RBFS) provide a simple way to construct numerical solutions with high accuracy. However, the linear systems arising from these methods are usually ill-conditioned, which poses a challenge for iterative solvers.

We construct preconditioners based on additive Schwarz methods to accelerate the solution process for solving boundary value problems on local spherical regions.

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1 Introduction

Let $\Omega$ be a simply connected local region with a smooth boundary $\partial \Omega$ on the unit sphere $S^n$ in $\mathbb{R}^{n+1}$. Let $L$ be a differential operator, and let $f$ and $g$ be two given functions in certain Sobolev spaces. We assume that the boundary value problem

$$Lu = f \text{ on } \Omega, \quad u = g \text{ on } \partial \Omega,$$

has a unique solution and that $L$ is self-adjoint.

Such boundary value problems arise naturally in geophysics and oceanography when scientists model a physical quantity on large scales. In these situations, the curvature of the Earth cannot be ignored, and a boundary value problem has to be formulated on a local region of the unit sphere. For example, the study of planetary-scale oceanographic flows in which oceanic eddies interact with topography such as ridges and land masses, or evolve in a closed basin, leads to the study of point vortices on the surface of the sphere with boundaries [2, 6]. Such vortex motions can be described as a Dirichlet problem on a subdomain of the sphere for the Laplace–Beltrami operator [1, 3].

Using a meshless method, we construct numerical solutions to (1) based on spherical radial basis functions. To accelerate the solution process, we introduce a preconditioner based on the additive Schwarz method. While in previous works, we considered pseudo-differential equations defined on the whole sphere [4, 7], in this article we focus on boundary value problems defined on local spherical regions.

2 Spherical RBFs

We assume that $\Phi : S^n \times S^n \rightarrow \mathbb{R}$ is a strictly positive definite kernel on $S^n$, that is

(i) $\Phi$ is continuous,

(ii) $\Phi(x, y) = \Phi(y, x)$ for all $x, y \in S^n$,

(iii) For any set of distinct points $X = \{x_1, \ldots, x_K\} \subset S^n$, the matrix $[\Phi(x_p, x_q)]$ is strictly positive-definite.

For mathematical analysis, sometimes it is convenient to expand the kernel $\Phi$ into a series of spherical harmonics [5]. The space of spherical harmonics of degree $\ell$ on $S^n$, denoted by $\mathcal{H}_\ell$, has an orthonormal basis

$$\{Y_{\ell,k} : k = 1, \ldots, N(n, \ell)\},$$
where
\[ N(n, 0) = 1 \quad \text{and} \quad N(n, \ell) = \frac{(2\ell + n - 1)\Gamma(\ell + n - 1)}{\Gamma(\ell + 1)\Gamma(n)} \quad \text{for} \ \ell \geq 1. \]

The kernel \( \Phi \) is expanded as
\[
\Phi(x, y) = \sum_{\ell=0}^{\infty} \sum_{k=1}^{N(n, \ell)} \hat{\phi}(\ell) Y_{\ell,k}(x) Y_{\ell,k}(y), \quad x, y \in S^n,
\]
where \( \{\hat{\phi}(\ell)\}_{\ell=0}^{\infty} \) is a sequence of positive real numbers satisfying \( \sum_{\ell=0}^{\infty} N(n, \ell) \hat{\phi}(\ell) < \infty \).

Every function \( f \in L^2(S^n) \) is also expanded in terms of spherical harmonics,
\[
f = \sum_{\ell=0}^{\infty} \sum_{k=1}^{N(n, \ell)} \hat{f}_{\ell,k} Y_{\ell,k}, \quad \hat{f}_{\ell,k} = \int_{S^n} f Y_{\ell,k} dS.
\]

Let us define the inner product
\[
\langle f, g \rangle_\Phi := \sum_{\ell=0}^{\infty} \sum_{k=0}^{N(n, \ell)} \frac{1}{\hat{\phi}(\ell)} \hat{f}_{\ell,k} \hat{g}_{\ell,k},
\]
and the associated norm \( \|f\|_\Phi = \sqrt{\langle f, f \rangle_\Phi} \). Let
\[
\mathcal{N}_\Phi := \{ f \in L^2(S^n) : \|f\|_\Phi < \infty \}.
\]
It can be shown that \( \mathcal{N}_\Phi \) is a reproducing kernel Hilbert space. For all \( f \in \mathcal{N}_\Phi \),
\[
\langle f, \Phi(\cdot, x) \rangle_\Phi = f(x) \quad \forall x \in S^n.
\] (2)

So \( \Phi \) is the reproducing kernel of \( \mathcal{N}_\Phi \).

3 A collocation method

Let \( X^{(I)} = \{x_1, x_2, \ldots, x_M\} \) be a set of scattered points in \( \Omega \) and let \( X^{(B)} = \{x_{M+1}, x_{M+2}, \ldots, x_N\} \) be a set of scattered points on \( \partial \Omega \). The uniformity of the point set \( X^{(I)} \) is measured by its mesh norm \( h = h_X \), and its separation radius \( q = q_X \), defined by
\[
h_X := \sup_{y \in \Omega} \min_{x \in X} \cos^{-1}(x \cdot y) \quad \text{and} \quad q_X := \frac{1}{2} \min_{x \neq y, x, y \in \Omega} \cos^{-1}(x \cdot y).\]
The angle $\cos^{-1}(\mathbf{x} \cdot \mathbf{y})$ is called the geodesic distance between two points $\mathbf{x}$ and $\mathbf{y}$ on the sphere.

Let

$$\varphi_j = \begin{cases} L_y \Phi(\cdot, \mathbf{x}_j), & j = 1, \ldots, M, \\ \Phi(\cdot, \mathbf{x}_j), & j = M + 1, \ldots, N. \end{cases}$$

Here $L_x$ (or $L_y$) denotes the operator $L$ acting on the first (or second) variable of the kernel $\Phi(\mathbf{x}, \mathbf{y})$. In this work, we restrict ourselves to a class of rotational invariant operators such that $L_x \Phi(\mathbf{x}, \mathbf{y}) = L_y \Phi(\mathbf{x}, \mathbf{y})$. This property holds for many operators frequently seen in practice, for example, the Laplace–Beltrami operator, the weakly-singular integral and hypersingular integral operators [7]. Due to this assumption, we write, for simplicity of notation, $L \Phi$ in place of $L_x \Phi$ or $L_y \Phi$.

Let

$$V = \text{span} \{ \varphi_1, \ldots, \varphi_N \}. \quad (3)$$

The collocation method to solve (1) consists of finding a $u_X \in V$ that solves

$$Lu_X(\mathbf{x}_k) = f(\mathbf{x}_k), \quad k = 1, \ldots, M; \quad (4a)$$
$$u_X(\mathbf{x}_k) = g(\mathbf{x}_k), \quad k = M + 1, \ldots, N. \quad (4b)$$

In view of (1) and (3) we deduce from (4a)–(4b) that

$$u_X = \sum_{j=1}^N c_j \varphi_j$$

where the coefficients $c_j$, $j = 1, \ldots, N$, are determined by

$$\sum_{j=1}^M c_j LL \Phi(\mathbf{x}_k, \mathbf{x}_j) + \sum_{j=M+1}^N c_j L \Phi(\mathbf{x}_k, \mathbf{x}_j) = f(\mathbf{x}_k), \quad k = 1, \ldots, M,$$
$$\sum_{j=1}^M c_j L \Phi(\mathbf{x}_k, \mathbf{x}_j) + \sum_{j=M+1}^N c_j \Phi(\mathbf{x}_k, \mathbf{x}_j) = g(\mathbf{x}_k), \quad k = M + 1, \ldots, N.$$

The above linear system is written in matrix form as

$$A \mathbf{c} = \mathbf{b} \quad (5)$$

where

$$A = \begin{bmatrix} B_{LL} & B_L \\ B_L & B \end{bmatrix}$$

with

$$B_{LL} = [LL \Phi(\mathbf{x}_k, \mathbf{x}_j)]_{\mathbf{x}_k, \mathbf{x}_j \in \mathcal{X}}.$$
Additive Schwarz methods

Let

\[ B_L = [L \Phi(x_k, x_j)]_{x_k \in X^{(l)}, x_j \in X^{(l)}}, \]

\[ B = [\Phi(x_k, x_j)]_{x_k, x_j \in X^{(l)}}, \]

and

\[ b = [f(x_1) \ldots f(x_M) \ g(x_{M+1}) \ldots g(x_N)]^T. \]

The matrix \( A \) is symmetric positive definite, so an iterative method can be used. It is often ill-conditioned, especially when the minimum separation radius \( q_X \) is small.

Before introducing fast iterative solvers for the linear system, let us rewrite our collocation equations (4a)–(4b) as a variational problem.

**Lemma 1** Equations (4a)–(4b) are equivalent to

\[ \langle u_X, \varphi_j \rangle_\Phi = \langle u, \varphi_j \rangle_\Phi, \quad j = 1, \ldots, N. \] (6)

**Proof:** Noting (2) we rewrite (4a)-(4b) as follows. For \( j = 1, \ldots, M \), since

\[ \langle u_X, \varphi_j \rangle_\Phi = \langle u_X, L \Phi(\cdot, x_j) \rangle_\Phi = \langle Lu_X, \Phi(\cdot, x_j) \rangle_\Phi = Lu_X(x_j) \]

and

\[ \langle L^{-1} f, \varphi_j \rangle_\Phi = \langle f, L^{-1} \varphi_j \rangle_\Phi = \langle f, L^{-1} L \Phi(\cdot, x_j) \rangle_\Phi = \langle f, \Phi(\cdot, x_j) \rangle_\Phi = f(x_j), \]

we rewrite (4a) as

\[ \langle u_X, \varphi_j \rangle_\Phi = \langle L^{-1} f, \varphi_j \rangle_\Phi = \langle u, \varphi_j \rangle_\Phi. \] (7)

Similarly, for \( j = M + 1, \ldots, N \), since \( \langle u_X, \varphi_j \rangle_\Phi = \langle u_X, \Phi(\cdot, x_j) \rangle_\Phi = u_X(x_j) \)

and \( \langle g, \varphi_j \rangle_\Phi = \langle g, \Phi(\cdot, x_j) \rangle_\Phi = g(x_j) \) we rewrite (4b) as

\[ \langle u_X, \varphi_j \rangle_\Phi = \langle g, \varphi_j \rangle_\Phi = \langle u, \varphi_j \rangle_\Phi. \] (8)

This lemma enables us to define the additive Schwarz method in the next section.

### 4 Additive Schwarz methods

A framework for the additive Schwarz method applied to elliptic PDEs defined on the whole sphere without boundary conditions was discussed by Le Gia et al. [4]. In this section, we propose a more general framework for boundary value problems on a subdomain of the unit sphere.
Additive Schwarz methods provide a fast solution to equations (4a)-(4b) by solving, in parallel, problems of smaller size. Let the space \( V \) be decomposed as
\[
V = V_0 + V_1 + \cdots + V_J + V_{J+1} + \cdots + V_K
\]
where we require that \( V_k \subset \text{span}\{\varphi_1, \ldots, \varphi_M\} \) for \( k = 0, \ldots, J \), and \( V_k \subset \text{span}\{\varphi_{M+1}, \ldots, \varphi_N\} \) for \( k = J + 1, \ldots, K \).

For \( k = 0, \ldots, K \), let \( P_k: V \to V_k \) be defined by
\[
\langle P_k w, \xi \rangle_\Phi = \langle w, \xi \rangle_\Phi \quad \text{for all} \quad \xi \in V_k \quad \text{and all} \quad w \in V.
\]

Let \( P = P_0 + P_1 + \cdots + P_K \). The additive Schwarz method applied to the collocation equations involves solving the equation
\[
Pu_X = h = \sum_{k=0}^{K} h_k,
\]
where for \( k = 0, \ldots, J \),
\[
\langle h_k, \xi \rangle_\Phi = \langle L^{-1} f, \xi \rangle_\Phi \quad \text{for all} \quad \xi \in V_k,
\]
and for \( k = J + 1, \ldots, K \)
\[
\langle h_k, \xi \rangle_\Phi = \langle g, \xi \rangle_\Phi \quad \text{for all} \quad \xi \in V_k.
\]

**Lemma 2** The approximate solution \( u_X \) is a solution to the variational equation (6) if and only if it is a solution to (10).

**Proof:** Suppose \( u_X \) solves (6). Then for \( k = 0, \ldots, J \), using (7) we obtain
\[
\langle P_k u_X, \xi \rangle_\Phi = \langle u_X, \xi \rangle_\Phi = \langle L^{-1} f, \xi \rangle_\Phi = \langle h_k, \xi \rangle_\Phi \quad \forall \xi \in V_k.
\]
So, \( P_k u_X = h_k \) for \( k = 0, \ldots, J \). Similarly, for \( k = J + 1, \ldots, K \), by using (8) we obtain
\[
\langle P_k u_X, \psi \rangle_\Phi = \langle u_X, \psi \rangle_\Phi = \langle g, \psi \rangle_\Phi = \langle h_k, \psi \rangle_\Phi \quad \forall \psi \in V_k.
\]
Hence
\[
Pu_X = \sum_{k=0}^{K} P_k u_X = \sum_{k=0}^{K} h_k = h,
\]
that is \( u_X \) satisfies (10). Conversely, suppose \( u_X \) solves (10). For \( j = 1, \ldots, N \),
\[
\langle u_X, \varphi_j \rangle_\Phi = \langle P^{-1} h, \varphi_j \rangle_\Phi = \langle h, P^{-1} \varphi_j \rangle_\Phi
\]
$$\begin{align*}
\sum_{k=0}^{K} \langle h_k, P^{-1} \varphi_j \rangle_{\Phi} &= \sum_{k=0}^{K} \langle h_k, P_k P^{-1} \varphi_j \rangle_{\Phi} \\
&= \sum_{k=0}^{J} \langle L^{-1} f, P_k P^{-1} \varphi_j \rangle_{\Phi} + \sum_{k=J+1}^{K} \langle g, P_k P^{-1} \varphi_j \rangle_{\Phi} \\
&= \sum_{k=0}^{K} \langle u, P_k P^{-1} \varphi_j \rangle_{\Phi} = \left\langle u, \sum_{k=0}^{K} P_k P^{-1} \varphi_j \right\rangle_{\Phi} = \langle u, \varphi_j \rangle_{\Phi}.
\end{align*}$$

In other words, \( u_X \) solves (6).

To put the abstract framework of the additive Schwarz method into practice, we need to construct a concrete algorithm to decompose the space \( V \) appropriately. The decomposition is defined from decompositions of the sets of collocation points \( X^{(I)} \) and \( X^{(B)} \).

The set \( X^{(I)} \) is decomposed by the following algorithm.

1. Put \( \Omega \) in a bounding box \( E = [L_{\min}, L_{\max}] \times [l_{\min}, l_{\max}] \) in spherical coordinates or in geographical coordinates.

2. Divide the box \( E \) into an \( m \times n \) grid for some given positive integers \( m \) and \( n \).

3. Enumerate the cells of the grid from 1 to \( J := mn \).

4. Let \( X_j := X^{(I)} \cap \text{cell}(j) \) for \( j = 1, \ldots, J \).

5. We choose from each \( X_j \) one point which is closest to the centre of \( \text{cell}(j) \) to form the set \( X_0 \).

The set \( X^{(B)} \subset \partial \Omega \) of boundary points is divided into subsets of the same cardinality.

To illustrate the algorithm, let \( \Omega \) be the interior of Australia; see Figure 1. Firstly, the domain \( \Omega \) is put into a bounding box \( E \) of \([110^\circ E, 160^\circ E] \times [10^\circ S, 40^\circ S]\) in geographical coordinates. Then \( E \) is sub-divided into \( 3 \times 5 = 15 \) cells. The points inside each cell form the subsets \( X_j \) for \( j = 1, \ldots, 15 \). From each subset \( X_j \), we choose one point which is closest to the centre of \( \text{cell}(j) \) to form the set \( X_0 \).

Given a partition of interior points \( X^{(I)} = \bigcup_{j=0}^{J} X_j \), we define 

\[ V_j := \text{span}\{ \varphi_m = L\Phi(\cdot, x_m) : x_m \in X_j \}, \quad j = 0, \ldots, J. \]

With another partition for the boundary points \( X^{(B)} = \bigcup_{k=J+1}^{K} X_k \), we define 

\[ V_k := \text{span}\{ \varphi_m = \Phi(\cdot, x_m) : x_m \in X_k \}, \quad k = J + 1, \ldots, K. \]
The additive Schwarz operator $P$ is now be considered a preconditioned solution operator. In terms of matrix equations

$$P = MA = \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \begin{bmatrix} B_{LL} & B_L \\ B_L & B \end{bmatrix}.$$ 

In practice, we need to compute the action of $M^{-1}$ on a residual $r \in V$. This consists of the solution of independent problems on each of the subspaces involved in the decomposition. The process is summarised in the following steps.

1. Correction of the global coarse set $X_0$:
   $$\text{find} \; u_0 \in V_0 \text{ satisfying } \langle u_0, \xi \rangle = \langle r, \xi \rangle \forall \xi \in V_0.$$ 

2. Corrections on the local interior sets $X_j$, $j = 1, \ldots, J$:
   $$\text{find} \; u_j \in V_j \text{ satisfying } \langle u_j, \xi \rangle = \langle r, \xi \rangle \forall \xi \in V_j.$$ 

3. Corrections on the local boundary sets $X_k$, $k = J + 1, \ldots, K$:
   $$\text{find} \; u_k \in V_k \text{ satisfying } \langle u_k, \psi \rangle = \langle r, \psi \rangle \forall \psi \in V_k.$$
4. The residual in the conjugate gradient is preconditioned by

\[ M^{-1}r := \sum_{j=0}^{J} u_j + \sum_{k=J+1}^{K} u_k. \]

5 Numerical experiments

Let us consider the boundary value problem:

\[ \begin{align*}
-\Delta^* u &= f \text{ in } \Omega \\
u &= g \text{ in } \partial\Omega.
\end{align*} \tag{11} \]

Here \( \Delta^* \) is the Laplace–Beltrami operator defined on the sphere \( S^2 \) in \( \mathbb{R}^3 \).

We choose \( f \) and \( g \) so that the exact solution is

\[ u(\theta, \phi) = \sin \theta \cos \phi + (2 \sin(2\theta) - \sin(4\theta)) \cos(3\phi), \quad \theta \in [0, \pi], \quad \phi \in [0, 2\pi). \]

The RBF used in the experiments is \( \Phi(x, y) = \rho(\sqrt{2 - 2x \cdot y}) \) with \( \rho(r) = (35r^2 + 18r + 3)(1 - r)^6 \). The point sets are taken from MAGSAT satellite data restricted to \( \Omega \), where \( \Omega \) is some local region of the Earth.

In the first experiment, we solve an academic problem on \( \Omega = \Omega_1 = [110^\circ E, 160^\circ E] \times [10^\circ S, 40^\circ S] \) in geographical coordinates. In the second experiment, we solve a more practical problem with \( \Omega = \Omega_2 \) being the interior of Australia (as in Figure 1).

We solve the matrix equation (5) using the conjugate gradient method with a relative tolerance of \( 10^{-7} \), that is the stopping criterion is

\[ \frac{\|Ae^{(m)} - b\|_{\ell_2}}{\|b\|_{\ell_2}} \leq 10^{-7}. \]

The conjugate gradient method is considered non-convergent when the number of iterations exceeds \( 20N \), where \( N \times N \) is the dimension of the matrix \( A \).

As is seen from the numerical results presented in Tables 1, 2 and 3, the Schwarz preconditioner significantly improves the CPU time and reduce the number of iterations of the conjugate gradient method. For the first experiment involving \( \Omega_1 \), the unpreconditioned conjugate gradient method applied to the problem is not convergent. For both examples, since the number of collocation points on the boundary \( X^{(B)} \) is rather small, we did not decompose the space span\{\( \varphi_{M+1}, \ldots, \varphi_N \)\} and hence \( K = J + 1 \) in both cases. It is observed that the condition number \( \kappa(P) \) of the additive Schwarz operator \( P \) seems to be independent of the number of subdomains \( J \).
Table 1: Numerical results for the boundary value problem (11) defined on $\Omega_1$ using preconditioned conjugate gradient (CG). The unpreconditioned CG does not converge in this example.
Table 2: Numerical results for (11) defined on $\Omega_2$ using preconditioned cg.

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Table 3: Numerical results for (11) defined on $\Omega_2$ using unpreconditioned cg.

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6 Conclusion

In this article we suggested a collocation method with RBFs for a boundary value problem in a local region on a sphere. The method is designed in such a way that the resulting matrix is symmetric and positive definite. (The method is sometimes called the symmetric collocation method in the RBF literature.) However, as is well known, the matrix is ill-conditioned. We provided a remedy by additive Schwarz preconditioners. The use of a symmetric collocation method requires that the preconditioner be designed properly so that the resulting system is still equivalent to the original problem. Lemma 2 which justifies this equivalence can be extended to any subdomain of a general Riemannian manifold equipped with a reproducing Hilbert space structure.

We carried out numerical experiments on a practical domain (namely, the interior of the Australian continent) to support our theory. The numerical results showed that the RBF collocation method with a preconditioned conjugate gradient method can be very competitive for solving boundary value problems on local spherical regions.

References


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