SHARP HIGH-FREQUENCY ESTIMATES FOR THE
HELMHOLTZ EQUATION AND APPLICATIONS TO
BOUNDARY INTEGRAL EQUATIONS

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Abstract. We consider three problems for the Helmholtz equation in interior and exterior domains in $\mathbb{R}^d$, ($d = 2, 3$): the exterior Dirichlet-to-Neumann and Neumann-to-Dirichlet problems for outgoing solutions, and the interior impedance problem. We derive sharp estimates for solutions to these problems that, in combination, give bounds on the inverses of the combined-field boundary integral operators for exterior Helmholtz problems.

1. Introduction

Proving bounds on solution of the Helmholtz equation

$$\Delta u + k^2 u = -f$$

(where $f$ is a given function and $k > 0$ is the wavenumber) has a long history. Nevertheless, the following problems have remained open.

(i) Proving sharp bounds on the Dirichlet-to-Neumann (DtN) or Neumann-to-Dirichlet (NtD) maps for outgoing solutions of the homogeneous Helmholtz equation (i.e. equation (1) with $f = 0$) in exterior nontrapping domains.

(ii) Proving sharp bounds on the solution of the interior impedance problem (IIP) for general domains, where this boundary value problem (BVP) consists of (1) posed in a bounded domain with the boundary condition

$$\frac{\partial u}{\partial n} - i\eta u = g$$

where $g$ is a given function and $\eta \in \mathbb{R} \setminus \{0\}$.

This paper fills these gaps in the literature.

The motivation for considering the exterior DtN and NtD maps for the Helmholtz equation is fairly clear, since these are natural objects to study in relation to scattering problems. The motivation for studying the IIP is two-fold:
(i) It has become a standard model problem used when designing numerical methods for solving the Helmholtz equation (see Section 5.1 below for further explanation), and to prove error estimates one needs bounds on the solution of the BVP.

(ii) The integral equations used to solve the exterior Dirichlet, Neumann, and impedance problems can also be used to solve the IIP; therefore, to prove bounds on the inverses of these integral operators, one needs to have bounds on the solution of the IIP – we discuss this more in §6 below.

This paper may be regarded as a sequel to [13] and [61] as it variously sharpens and generalizes estimates obtained in those works. We will refer to these paper for many of the basic results. Although the results proved here hold for any dimension \( d \geq 2 \), we state them only in dimensions 2 and 3, firstly since these are the most interesting for applications, and secondly since this avoids re-proving background material only stated in these low dimensions.

1.1. Statement of the main results. Let \( \Omega_- \subset \mathbb{R}^d \), \( d = 2, 3 \), be a bounded, Lipschitz open set with boundary \( \Gamma := \partial \Omega_- \), such that the open complement \( \Omega_+ := \mathbb{R}^d \setminus \Omega_- \) is connected. Let \( \gamma_\pm \) denote the trace operators from \( \Omega_\pm \) to \( \Gamma \), let \( \partial_\pm n \) denote the normal derivative trace operators, and let \( \nabla_\Gamma \) denote the surface gradient operator on \( \Gamma \). Let \( B_R := \{x : |x| < R \} \).

**Definition 1.1 (Nontrapping).** We say that \( \Omega_- \subset \mathbb{R}^d \), \( d = 2, 3 \) is nontrapping if \( \Gamma \) is smooth (\( C^\infty \)) and, given \( R > \sup_{x \in \Omega_-} |x| \), there exists a \( T(R) < \infty \) such that all the billiard trajectories (in the sense of Melrose–Sjöstrand [48]) that start in \( \Omega_+ \cap B_R \) at time zero leave \( \Omega_+ \cap B_R \) by time \( T(R) \).

**Definition 1.2 (Nontrapping polygon).** If \( \Omega_- \subset \mathbb{R}^2 \) is a polygon we say that it is a nontrapping polygon if (i) no three vertices are colinear, and (ii), given \( R > \sup_{x \in \Omega_-} |x| \), there exists a \( T(R) < \infty \) such that all the billiard trajectories that start in \( \Omega_+ \cap B_R \) at time zero and miss the vertices leave \( \Omega_+ \cap B_R \) by time \( T(R) \). (For a more precise statement of (ii) see [7, §5].)

**Definition 1.3 (Star-shaped).** Let \( \Omega_- \subset \mathbb{R}^d \), \( d = 2, 3 \), be a bounded, Lipschitz open set.

(i) we say that \( \Omega_- \) is star-shaped if \( x \cdot n(x) \geq 0 \) for every \( x \in \Gamma \) for which \( n(x) \) is defined (where \( n(x) \) is the normal to \( x \in \Gamma \)).

(ii) we say that \( \Omega_- \) is star-shaped with respect to a ball if there exists a constant \( c > 0 \) such that \( x \cdot n(x) \geq c \) for every \( x \in \Gamma \) for which \( n(x) \) is defined.
Theorem 1.4 (Bounds on the exterior DtN map). Let \( u \in H^1_{\text{loc}}(\Omega_+) \) satisfy the Helmholtz equation
\[
\Delta u + k^2 u = 0 \quad \text{in } \Omega_+ \tag{3}
\]
for \( k \in \mathbb{R} \setminus \{0\} \) and the Sommerfeld radiation condition
\[
\frac{\partial u}{\partial r} - ik u = o \left( \frac{1}{r^{(d-1)/2}} \right) \quad \tag{4}
\]
as \( r := |x| \to \infty \), uniformly in \( \hat{x} := x/r \). If either \( \Omega_+ \) is nontrapping (in the sense Definition 1.1) or \( \Omega_- \) is a nontrapping polygon (in the sense of Definition 1.2) or \( \Omega_- \) is Lipschitz and star-shaped (in the sense of Definition 1.3(i)), then, given \( k_0 > 0 \),
\[
\| \partial^+ u \|_{H^{-1/2}(\Gamma)} \lesssim |k| \| \gamma^+ u \|_{H^{1/2}(\Gamma)}, \tag{5}
\]
for all \( |k| \geq k_0 \). Furthermore, if \( \gamma^+ u \in H^1(\Gamma) \) then \( \partial^+_n u \in L^2(\Gamma) \) and, given \( k_0 > 0 \),
\[
\| \partial^+_n u \|_{L^2(\Gamma)} \lesssim \| \nabla_{\Gamma}(\gamma^+ u) \|_{L^2(\Gamma)} + |k| \| \gamma^+ u \|_{L^2(\Gamma)}, \tag{6}
\]
for all \( |k| \geq k_0 \).

Theorem 1.5 (Bounds on the NtD map). Let \( \Omega_+ \) be nontrapping (in the sense Definition 1.1) and let \( u \in H^1_{\text{loc}}(\Omega_+) \) satisfy the Helmholtz equation (3) and the Sommerfeld radiation condition (4). Let \( \beta = \frac{2}{3} \) in the case when \( \Gamma \) has strictly positive curvature, and \( \beta = \frac{1}{3} \) otherwise.

Then, given \( k_0 > 0 \),
\[
\| \gamma^+ u \|_{H^{1/2}(\Gamma)} \lesssim |k|^{1-\beta} \| \partial^+_n u \|_{H^{-1/2}(\Gamma)}, \tag{7}
\]
for all \( |k| \geq k_0 \). Furthermore, if \( \partial^+_n u \in L^2(\Gamma) \) then \( \gamma^+ u \in H^1(\Gamma) \) and, given \( k_0 > 0 \),
\[
\| \nabla_{\Gamma}(\gamma^+ u) \|_{L^2(\Gamma)} + |k| \| \gamma^+ u \|_{L^2(\Gamma)} \lesssim |k|^{1-\beta} \| \partial^+_n u \|_{L^2(\Gamma)}, \tag{8}
\]
for all \( |k| \geq k_0 \).

By considering the specific examples of \( \Gamma \) the unit circle (in 2-d) and the unit sphere (in 3-d) and using results about the asymptotics of Bessel and Hankel functions, it was shown in [61, Lemmas 3.10, 3.12] that the bounds (5) and (6) are sharp, and that (7) and (8) are sharp in the case of strictly positive curvature.

We prove the DtN bound (6) and can then get a bound on the DtN map between a range of Sobolev spaces by interpolation. Of this range, the bound (5) is the most interesting (since it is between the natural...
trace spaces for solutions of the Helmholtz equation) and thus we state it explicitly; similarly for (8) and (7).

Our next result concerns the IIP under the following assumption about the impedance parameters \( \eta \). We permit a more general assumption on \( \eta \) than that specified in the introduction: it can be variable, and need only have nonzero real part with a linear rate of growth in \( k \).

**Assumption 1.6 (A particular class of \( \eta \)).** \( \eta(x) := a(x)k + ib(x) \) where \( a, b \) are real-valued \( C^\infty \) functions on \( \Gamma \), \( b \geq 0 \) on \( \Gamma \), and there exists an \( a_- > 0 \) such that either

\[
\begin{align*}
    a(x) &\geq a_- > 0 \quad \text{for all } x \in \Gamma \quad \text{or} \\
    -a(x) &\geq a_- > 0 \quad \text{for all } x \in \Gamma.
\end{align*}
\]

For purposes of obtaining estimates valid down to \( k = 0 \) (and in particular, to make contact with applications in the work of Epstein, Greengard, and Hagstrom [20]) we will also state another, stronger set of hypotheses on \( \eta \).

**Assumption 1.7 (Another class of \( \eta \)).** \( \eta(x) := a(x)k + ib(x) \) where \( a, b \) are real-valued \( C^\infty \) functions on \( \Gamma \) and there exists \( a_- > 0, b_- > 0 \) such that

\[
\begin{align*}
    a(x) &\geq a_- > 0 \quad \text{for all } x \in \Gamma \quad \text{and} \\
    b(x) &\geq b_- > 0 \quad \text{for all } x \in \Gamma.
\end{align*}
\]

In our discussion of the impedance problem, we use \( \Omega \) to denote the domain where the IIP is posed (instead of \( \Omega_- \)), since we do not need the restriction that we imposed on \( \Omega_- \) that the open complement is connected.

**Theorem 1.8 (Bounds on the solution to the interior impedance problem).** Let \( \Omega \) be a bounded \( C^\infty \) open set in 2- or 3-dimensions with boundary \( \Gamma \). Given \( g \in L^2(\Gamma) \), \( f \in L^2(\Omega) \), and \( \eta \) satisfying Assumption 1.6, let \( u \in H^1(\Omega) \) be the solution to the interior impedance problem

\[
\Delta u + k^2 u = -f \quad \text{in } \Omega \quad \text{and} \quad \partial_n u - i\eta \gamma u = g \quad \text{on } \Gamma. \tag{9}
\]

Then, given \( k_0 > 0 \),

\[
\|\nabla u\|_{L^2(\Omega)} + |k| \|u\|_{L^2(\Omega)} \lesssim \|f\|_{L^2(\Omega)} + \|g\|_{L^2(\Gamma)} \tag{10}
\]

for all \( |k| \geq k_0 \).

The bound (10) is sharp. Indeed, in [61, Lemma 4.12] it was proved that given any bounded Lipschitz domain, there exists an \( f \) such that the solution of the IIP with \( g = 0 \) and this particular \( f \) satisfies \( |k|\|u\|_{L^2(\Omega)} \gtrsim \|f\|_{L^2(\Omega)} \). Furthermore Lemma 5.5 shows that if \( \Omega \) is a ball and \( f = 0 \) then there exists a \( g \) such that the solution of the IIP with \( f = 0 \) and this particular \( g \) satisfies \( |k|\|u\|_{L^2(\Omega)} \gtrsim \|g\|_{L^2(\Gamma)} \).
Note that Assumption 1.6 includes the cases $\eta = \pm k$, and thus the bound (10) holds for the two most-commonly occurring impedance boundary conditions, namely $\partial_n u - ik\gamma u = g$ and $\partial_n u + ik\gamma u = g$.

For our application of this result to integral equations, we state a result on the Dirichlet trace of the solution of the IIP.

**Corollary 1.9 (Bound on the interior impedance-to-Dirichlet map).** Let $\Omega$ be a bounded $C^\infty$ domain in 2- or 3-d with boundary $\Gamma$. Given $g \in L^2(\Gamma)$ and $\eta$ satisfying Assumption 1.6, let $u \in H^1(\Omega)$ be the solution to the interior impedance problem (9) with $f = 0$. Then, given $k_0 > 0$,

$$\|\nabla_\Gamma (\gamma u)\|_{L^2(\Gamma)} + |k| \|\gamma u\|_{L^2(\Gamma)} \lesssim \|g\|_{L^2(\Gamma)}$$

for all $|k| \geq k_0$.

Shifting to a slightly different perspective, having proved the bound (10) for real $k$ it is natural to impose the homogeneous impedance boundary condition $\partial_n u - i\eta\gamma u = 0$ and consider the operator family $(\Delta + k^2)^{-1}$ for $k \in \mathbb{C}$. That is, we define $(\Delta + k^2)^{-1} : L^2(\Omega) \to L^2(\Omega)$ by $(\Delta + k^2)^{-1}f = u$, where $u$ is the solution to $(\Delta + k^2)u = f$ satisfying $\partial_n u - i\eta\gamma u = 0$. If $\eta$ satisfies Assumption (1.6) then $(\Delta + k^2)^{-1}$ is well defined when $k \in \mathbb{R} \setminus \{0\}$. Meanwhile, the strict positivity of $a$ implies that $(\Delta + k^2)^{-1}$ is well defined and holomorphic for $\text{Im} k > 0$. We can then use a simple perturbation argument to show the existence of regions beneath the real axis free of poles (the equivalent of “resonances” in this compact, non-self-adjoint setting); if we strengthen our assumptions to strict positivity of $b$, this yields a full pole-free strip beneath the real axis, while mere nonnegativity leaves the possibility of a singularity at $k = 0$.

The following result is stated with the stronger hypothesis and consequent pole-free strip.

**Theorem 1.10 (Pole-free strip beneath the real axis).** The operator family $(\Delta + k^2)^{-1} : L^2(\Omega) \to L^2(\Omega)$ with boundary condition $\partial_n u - i\eta\gamma u = 0$, where $\eta$ satisfies Assumption 1.7, is holomorphic on $\text{Im} k > 0$. Furthermore there exist an $\varepsilon > 0$ such that $(\Delta + k^2)^{-1}$ extends from the upper-half plane to a holomorphic operator family on $\text{Im} k > -\varepsilon$, satisfying the uniform estimate

$$\|(\Delta + k^2)^{-1}\|_{L^2(\Omega) \to L^2(\Omega)} \lesssim (1 + |k|)^{-1}$$

in that region.
1.2. Discussion of previous results related to Theorems 1.4–1.8. The only previously-existing sharp bound for one of the DtN and NtD maps is the bound (6) proved when $\Omega_-$ is a Lipschitz domain that is star-shaped with respect to a ball (in the sense of Part (ii) of Definition 1.3). This bound was proved in [51] without the smoothness requirements of the boundary explicitly stated, but the some techniques apply to Lipschitz domains, modulo some additional technical work; see [61, Remark 3.8] and [49, Appendix A]. Non-sharp bounds on the DtN and NtD maps were proved in [3], [38], and [61]; see [61, §1.2] for a discussion of all these results.

Of the bounds on the IIP in the literature, the only previously-existing sharp result was that (10) holds when $\Omega$ is Lipschitz and star-shaped with respect to a ball. This was proved in 2-d when $\Gamma$ is piecewise smooth by Melenk [44, Proposition 8.1.4] and in 3-d by Cummings and Feng [15, Theorem 1]. The technical work referred to above can then be used to establish the bound when $\Gamma$ is Lipschitz (see, e.g., [25, Theorem 2.6] where the analogue of this bound is proved for a more general class of wavenumbers). By the discussion immediately after Theorem 1.8, this bound for star-shaped Lipschitz domains is sharp. Bounds for general Lipschitz domains with positive powers of $k$ in front of both $\|f\|_{L^2(\Omega)}$ and $\|g\|_{L^2(\Gamma)}$ were obtained in [23, Theorems 3.6 and 4.7], [21, Theorem 2.4], and [61, Theorem 1.6]; see [61, §1.2] for more discussion.

1.3. Application of the above results to integral equations. As mentioned above, the results of Theorems 1.4, 1.5, and 1.8 can be applied to integral equations. Our main result in this direction concerns the standard integral equation used to solve the Helmholtz exterior Dirichlet problem.

When $u$ is the solution to the Helmholtz exterior Dirichlet problem, the Neumann trace of $u$, $\partial_n^+ u$, satisfies the integral equation

$$A_{k,\eta}'(\partial_n^+ u) = f_{k,\eta}$$

on $\Gamma$, where the integral operator $A_{k,\eta}'$ is the so-called combined-potential or combined-field integral operator (defined by (69) below), $f_{k,\eta}$ is given in terms of the known Dirichlet data $\gamma_+ u$ (see (68)).

Usually the parameter $\eta$ is a real constant different from zero, but in fact $\eta$ is also allowed to be a function of position on $\Gamma$ – we mention this because our result below allows for this possibility.

We introduce the notation that $P_{DN}^+$ denotes the exterior DtN map, as a mapping from $H^{s+1/2}(\Gamma) \rightarrow H^{s-1/2}(\Gamma)$ for $|s| \leq 1/2$, and $P_{ItD}^{-\eta}$ denotes the interior impedance-to-Dirichlet map, as a mapping from
\[ H^{s-1/2}(\Gamma) \to H^{s-1/2}(\Gamma) \text{ for } |s| \leq 1/2 \text{ (see \S 2.1 below and [11, Theorems 2.31 and 2.32] for details on how these maps are defined for these ranges of spaces).} \]

The inverse of \( A'_{k,\eta} \) can be written in terms of the exterior DtN map \( P^+_{DtN} \) and interior impedance to Dirichlet map \( P^-_{ItD} \) as follows

\[
(A'_{k,\eta})^{-1} = I - (P^+_{DtN} - i\eta)P^-_{ItD}; \tag{14}
\]

this decomposition is implicit in much of the work on the combined-potential operator \( A'_{k,\eta} \), but (to the authors’ knowledge) was first written down explicitly in [11, Theorem 2.33]. We give another, more intuitive proof, of this result in Lemma 6.1 below.

The operator \( A'_{k,\eta} \) is usually considered as a operator from \( L^2(\Gamma) \) to itself (the reasons for this are explained in \S 6) and the bounds on the exterior DtN map and interior impedance-to-Dirichlet map in Theorem 1.4 and Corollary 1.9 immediately yield the following bound on \( \| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \).

**Theorem 1.11.** Let \( \Omega_+ \subset \mathbb{R}^d \), \( d = 2, 3 \), be a nontrapping domain and suppose that \( \eta \) satisfies Assumption 1.6. Then, given \( k_0 > 0 \),

\[
\| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim 1 \tag{15}
\]

for all \( |k| \geq k_0 \).

Since the proof is so short, we include it in this introduction. The spaces \( H^1_k(\Gamma) \) used below are weighted Sobolev spaces defined in \S 2 (in particular, see equation (20)).

**Proof.** The decomposition (14) implies that

\[
\| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \leq 1 + \| P^+_{DtN} \|_{H^1_k(\Gamma) \to L^2(\Gamma)} \| P^-_{ItD} \|_{L^2(\Gamma) \to H^1_k(\Gamma)} + |\eta| \| P^-_{ItD} \|_{L^2(\Gamma) \to L^2(\Gamma)}.
\]

Theorem 1.4 implies that \( \| P^+_{DtN} \|_{H^1_k(\Gamma) \to L^2(\Gamma)} \lesssim 1 \) and Corollary 1.9 implies that \( \| P^-_{ItD} \|_{L^2(\Gamma) \to H^1_k(\Gamma)} \lesssim 1 \) (and thus \( \| P^-_{ItD} \|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim |k|^{-1} \)). These results, along with the assumption on \( \eta \), immediately give (15). \( \square \)

We make two immediate remarks regarding Theorem 1.11.

1. The bound (15) is sharp, since it was proved in [10, Theorem 4.3] that \( \| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma)} \geq 2 \) when part of \( \Gamma \) is \( C^1 \) and \( d = 2, 3 \).
2. In this paper we focus on the direct integral equation for the exterior Dirichlet problem, i.e. the equation where the unknown has an immediate physical meaning (in the case, it is the Neumann trace \( \partial_n^\perp u \)) but an analogous bound to (15) holds for the inverse of the operator involved in the standard indirect integral.
equation (where the unknown of the integral equation does not have an immediate physical meaning); see, e.g., [11, Remark 2.24, §2.6].

There have been two previous upper bounds on \( \| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \) proved in the literature; the bound

\[
\| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim 1 + \frac{k}{|\eta|} \tag{16}
\]

when \( \Omega_- \) is a 2- or 3-d Lipschitz domain that is star-shaped with respect to a ball and \( \eta \in \mathbb{R} \setminus \{0\} \) was proved in [13, Theorem 4.3] using the Morawetz-Ludwig DtN bound and Melenk’s bound on the IIP, both discussed in §1.2. Furthermore, using non-sharp bounds on \( P^+_{DtN} \) and \( P^-_{ItD} \), the bound

\[
\| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim k^{5/4} \left(1 + \frac{k^{3/4}}{|\eta|}\right) \tag{17}
\]

for \( \eta \in \mathbb{R} \setminus \{0\} \) was proved in [61, Theorem 1.11] when either \( \Omega_- \) is a 2- or 3-d nontrapping domain, or \( \Omega_- \) is a nontrapping polygon.

An immediate application of the bound (15) is the following. An error analysis of the \( h \)-boundary element method (i.e. the Galerkin method using subspaces consisting of piecewise polynomials with fixed degree) applied to the equation (13) was conducted in [27]. This analysis required \( \| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim 1 \), and so covered the case when \( |\eta| \sim k \) and \( \Omega_- \) is star-shaped with respect to a ball, using the bound (16). Thanks to the bound (15), however, this analysis is now valid when \( \Omega_+ \) is nontrapping and \( \eta \) satisfies Assumption 1.6. (Note that the error analysis of the \( hp \)-boundary element method conducted in [40], [45] only requires \( \| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim k^\beta \) for some \( \beta > 0 \), and thus the bound (17) is sufficient for this analysis to be valid for nontrapping domains.)

The bound (15), used in conjunction with the recent results of Galkowski-Smith and Galkowski [24], [29], on essentially the norm of \( A'_{k,\eta} \), almost completes the study of the conditioning of \( A'_{k,\eta} \) in the high-frequency limit, i.e., the study of

\[
\text{cond}(A'_{k,\eta}) := \| A'_{k,\eta} \|_{L^2(\Gamma) \to L^2(\Gamma)} \| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \tag{18}
\]

for \( k \) large. This study was initiated back in the 80s for the case when \( \Omega_- \) is a ball [36], [37], [1], with the main question considered being how one should choose the parameter \( \eta \) to minimize the condition number. The first works considering more domains other than balls (and justifying the standard choice of \( \eta \sim k \) for these) were [10], [13].
We discuss the implications of Theorem 1.11 and [29] on the condition number of $A'_{k,\eta}$ and the choice of $\eta$ in §7.

So far we have only discussed integral equations for the exterior Dirichlet problem. The case of the exterior Neumann problem is more subtle, and we refer the reader to §6.2–§6.3 where this is discussed.

2. Notation and preliminaries

Let $\Omega_+ \subset \mathbb{R}^d$, $d \geq 2$, be a bounded, Lipschitz open set with boundary $\Gamma := \partial \Omega_+$, such that the open complement $\Omega_+ := \mathbb{R}^d \setminus \Omega_-$ is connected. We denote the exterior and interior traces by $\gamma_\pm$, and the exterior and interior normal-derivative traces by $\partial^n_\pm$. The symbol $\chi$ will denote a function in $C^\infty_c(\Omega_+)$ that equals one in a neighbourhood of $\Omega_+$. Additional assumptions about the support of particular cutoffs will be stated explicitly.

The symbol $\Delta$ denotes the (nonpositive) Laplacian and $\square$ denotes the wave operator $\partial_t^2 - \Delta$.

Given a function $u \in C^1(\mathbb{R}^d \setminus \overline{B}_{R_0})$ for some $R_0 > 0$ and given $\lambda \in \mathbb{C}$, we say that $u$ satisfies the Sommerfeld radiation condition with spectral parameter $\lambda$ if

$$\frac{\partial u}{\partial r} - i\lambda u = o\left(\frac{1}{r^{(d-1)/2}}\right)$$

(19)

as $r := |x| \to \infty$, uniformly in $\hat{x} := x/r$.

We define the weighted norm

$$\|u\|_{H^s_k(X)} := \|\nabla u\|_{L^2(X)} + k^2\|u\|_{L^2(X)}.$$ (20)

(we use this notation with $X$ either $\Omega_+$, $\Omega_-$, or $\Gamma$; in the latter case the gradient is to be understood as the surface gradient $\nabla_\Gamma$).

More generally, for $s \in \mathbb{R}$ we let $H^s_k(X)$ denote the weighted Sobolev space obtained by interpolation and duality from the spaces of positive integer order

$$H^m_k(X) = \{u \in L^2(X) : |k|^{m-|\alpha|}D^\alpha u \in L^2(X), \text{ for all } |\alpha| \leq m\}.$$ As usual (see e.g. [67, §4.4]) we may identify these spaces on manifolds with boundary with the quotient space

$$H^s_k(\Omega_\pm) = \{u \in H^s_k(\mathbb{R}^n) \setminus \{u : u|_{\Omega_\pm} = 0\}\}.$$ An easy interpolation (see, e.g., [12]) shows that an equivalent norm on $H^s_k(X)$ for $s > 0$ is $\|\bullet\|_{H^s} + |k|^s\|\bullet\|_{L^2}$, and we will use this fact freely below.

We will also have occasion to consider domain of the self-adjoint operator $(-\Delta + k^2)^{s/2}$, with $\Delta$ denoting the (nonpositive) Laplacian with Neumann or Dirichlet boundary conditions and $s \geq 0$. We let
\( \mathcal{D}_{N,k} \) resp. \( \mathcal{D}_{D,k} \) denote these respective domains; for negative \( s \) the spaces are defined by duality: \( \mathcal{D}_{s,k} = (\mathcal{D}_{-s,k})^* \). As in [67, §5.A], we note that \( H^s_k(\Omega_\pm) = \mathcal{D}^s_N(\Omega_\pm) \), \( s \in [0, 1] \).

(21)

The norm with no subscript attached, \( \| \cdot \| \), will denote the \( L^2 \) norm throughout.

The following lemma connects Sobolev regularity in space-time to weighted Sobolev regularity following Fourier transform. Let \( F^{-1} \) denote the inverse Fourier transform taking the time variable to frequency variable \( k \).

Lemma 2.1. Let \( I \subset \mathbb{R} \) be a bounded open interval. There exist \( C_I \) such that

\[
\| F_{t \to k} u(k, x) \|_{H^\alpha_k(X)} \leq C_I \| u \|_{H^\alpha(I \times X)}
\]

for every \( u \in H^\alpha(\mathbb{R} \times X) \) supported in \( I \times X \).

The proof is simply intertwining the elliptic operator \((\partial_t^2 + \Delta)\) with the Fourier transform to obtain the result for \( \alpha \in \mathbb{N} \), followed by interpolation and duality for the general case.

2.1. Preparatory results for proving Theorems 1.4 and 1.5 (the DtN and NtD bounds). The following interpolation result (which appears as [61, Lemma 2.3]) shows that the DtN bound (5) follows from (6), and the NtD bound (7) follows from (8). To state this result, we denote the DtN map in \( \Omega_+ \) by \( P_{DtN}^+ \) and the NtD map by \( P_{NtD}^+ \) (following the notation in [11, §2.7]). \( P_{DtN}^+ \) is defined as a map from \( H^{1/2}(\Gamma) \) to \( H^{-1/2}(\Gamma) \) by standard results about the solvability of the exterior Dirichlet problem and the definition of the normal derivative, and the regularity result of Nečas stated as Lemma 2.3 below implies that \( P_{DtN}^+ \) can be extended to a map from \( H^1(\Gamma) \) to \( L^2(\Gamma) \). Analogous arguments hold for \( P_{NtD}^+ \).

Lemma 2.2 ([61]). With \( \Omega_+ \), \( P_{DtN}^+ \), and \( P_{NtD}^+ \) defined above,

\[
\| P_{DtN}^+ \|_{H^{1/2}(\Gamma) \to H^{-1/2}(\Gamma)} \leq \| P_{DtN}^+ \|_{H^1(\Gamma) \to L^2(\Gamma)}
\]

and analogously,

\[
\| P_{NtD}^+ \|_{H^{-1/2}(\Gamma) \to H^{1/2}(\Gamma)} \leq \| P_{NtD}^+ \|_{L^2(\Gamma) \to H^1(\Gamma)}.
\]

(Note that an analogous result holds for the interior impedance-to-Dirichlet map, and thus the bound in Corollary 1.9 implies a bound on this map from \( H^{-1/2}(\Gamma) \) to \( H^{1/2}(\Gamma) \), but we do not need this latter result in this paper.)
Having reduced the problem of obtaining the DtN and NtD bounds in Theorems 1.4 and 1.5 to the problem of obtaining the bounds between the spaces $H^1(\Gamma)$ and $L^2(\Gamma)$, we now use the well-known fact that a Rellich-type identity can be used to bound the (highest order terms of the) DtN and NtD maps, modulo terms in the domain. The next lemma is a restatement of Nečas’ result for strongly elliptic systems (see [52, §5.1.2, 5.2.1], [43, Theorem 4.24]) applied to the specific case of the Helmholtz equation, where we have kept track of the dependence of each term on $k$ (see [61, Lemma 3.5] for details).

**Lemma 2.3 (DtN and NtD bounds in $H^1(\Gamma)-L^2(\Gamma)$ modulo terms in the domain).** With $\Omega_+$ and $\chi$ as above, given $f \in L^2_{\text{comp}}(\Omega_+)$, let $u \in H^1_{\text{loc}}(\Omega_+)$ be a solution to $\Delta u + k^2 u = -f$.

(i) If $\gamma_+ u \in H^1(\Gamma)$ then $\partial^+_n u \in L^2(\Gamma)$ and
\[
\|\partial^+_n u\|_{L^2(\Gamma)}^2 \lesssim \|\nabla \gamma_+(u)\|_{L^2(\Gamma)}^2 + \|\chi u\|_{H^1(\Omega_+)}^2 + \|f\|_{L^2(\Omega_+)}^2. \tag{22}
\]

(ii) If $\partial^+_n u \in L^2(\Gamma)$ then $\gamma_+ u \in H^1(\Gamma)$ and
\[
\|\nabla \gamma_+(u)\|_{L^2(\Gamma)}^2 \lesssim \|\partial^+_n u\|_{L^2(\Gamma)}^2 + k^2 \|\gamma_+ u\|_{L^2(\Gamma)}^2 + \|\chi u\|_{H^1(\Omega_+)}^2 + \|f\|_{L^2(\Omega_+)}^2. \tag{23}
\]

Therefore, to prove the bounds in Theorem 1.4 it is sufficient to prove that, if $u \in H^1_{\text{loc}}(\Omega_+)$ is the solution to the exterior Dirichlet problem for the homogeneous Helmholtz equation, with $H^1$-Dirichlet boundary data $g_D$, then
\[
\|\chi u\|_{H^1(\Omega_+)} \lesssim \|\gamma_+ u\|_{H^1(\Gamma)}. \tag{24}
\]

Similarly, to prove the bounds in Theorem 1.5 it is sufficient to prove that, $u \in H^1_{\text{loc}}(\Omega_+)$ is the solution to the exterior Neumann problem for the homogeneous Helmholtz equation, with $L^2$-Neumann boundary data $g_N$, then
\[
\|\gamma_+ u\|_{L^2(\Gamma)} \lesssim k^{-\beta} \|\partial^+_n u\|_{L^2(\Gamma)} \quad \text{and} \quad \|\chi u\|_{H^1(\Omega_+)} \lesssim k^{1-\beta} \|\partial^+_n u\|_{L^2(\Gamma)}
\]
(we’ll actually prove the stronger result that the second bound holds with a smaller power of $k$ on the right-hand side, but this will not affect the bound on the NtD map). The asymmetry between what we need to prove for the Neumann problem versus what we need to prove for the Dirichlet problem is due to the fact that only the $H^1$-semi norm of the Dirichlet trace is controlled in (23), which is due to the structure of the Rellich identity (see, e.g., [61, Equation 3.13]).

Finally, in our proof of the NtD estimates we will need the following lemma. It is perhaps easiest to state this in terms of norms of $u$ over $\Omega_R := \Omega_+ \cap B_R$, where $B_R := \{x : |x| < R\}$, but the result could be
translated into norms of $\chi u$ over $\Omega_+$ for appropriate cut-off functions $\chi$.

**Lemma 2.4 (Bounding the $H^1$ norm via the $L^2$ norm and the data).** Given $f \in L^2_{\text{comp}}(\Omega_+)$, let $u \in H^1_\text{loc}(\Omega_+)$ be a solution of the Helmholtz equation $\Delta u + k^2 u = -f$ in $\Omega_+$. Then, given $R > \sup_{x \in \Omega_-} |x|$ and $k_0 > 0$,

$$\|\nabla u\|^2_{L^2(\Omega_R)} \lesssim \langle k \rangle^2 \|u\|^2_{L^2(\Omega_{R+1})} + \langle k \rangle^{-2} \|f\|^2_{L^2(\Omega_+)} + \|\gamma u\|_{L^2(\Gamma)} \|\partial_n u\|_{L^2(\Gamma)}$$

for all $k \geq k_0$. If $\eta$ or $-\eta$ satisfies the stronger hypothesis Assumption 1.7 then the result holds for all $k \in \mathbb{R}$.

The result when one of $\gamma u$ and $\partial_n u$ is zero is proved in [61, Lemma 2.2]; a similar result appears in [50, Lemma 1].

3. **Exterior Dirichlet-to-Neumann estimates**

In this section we prove Theorem 1.4, i.e., a bound on the exterior Dirichlet-to-Neumann map for solutions of the Helmholtz equation satisfying the Sommerfeld radiation condition.

The methods used here will be completely in the setting of stationary scattering theory, i.e., we will never have recourse to energy estimates for solutions to the wave equation (which is, of course, connected via Fourier transform). The energy estimates that we present are more widely known in this latter setting, however—cf. Hörmander [32, §24.1] as well as the more general estimates of Kreiss and Sakamoto in the context of general hyperbolic systems with a boundary condition satisfying the uniform Lopatinski condition [35], [57], [58]. (In contrast, when dealing with the Neumann-to-Dirichlet operator below, we need to use results known only in the wave equation setting.)

More specifically, the method we use to prove Theorem 1.4 consists of a “gluing” argument, where estimates for the DtN map for a lower-order “perturbation” of the Helmholtz equation are used in conjunction with the resolvent estimate for the problem with homogeneous boundary conditions. This argument was first used in [38], and later refined in [61]. Both these previous works using the equation $\Delta w - k^2 w = 0$ as the lower-order perturbation, and obtained non-sharp bounds on the Helmholtz DtN map. Here we use the equation $\Delta w + (k^2 + ik)w = 0$ as the lower-order perturbation, and this change is sufficient to prove the sharp result.

Before we begin, it is helpful to recall the following resolvent estimates for the Dirichlet problem (all but one of which hold for the Neumann problem as well).
**Theorem 3.1 (Resolvent estimates).** Let $f \in L^2(\Omega_+)\text{ have compact support, and let } u \in H^1_{\text{loc}}(\Omega_+)$ be a solution to the Helmholtz equation

$$\Delta u + k^2 u = -f \text{ in } \Omega_+ \text{ that satisfies the Sommerfeld radiation condition (4) (with } \lambda = k) \text{ and the boundary condition } \gamma_+ u = 0. \text{ If either}

(a) $\Omega_+$ is a 2- or 3-d nontrapping domain (in the sense of Definition 1.1)

(b) $\Omega_-$ is a nontrapping polygon (in the sense of Definition 1.2), or

(c) $\Omega_-$ is a 2- or 3-d Lipschitz domain that is star-shaped (in the sense of Definition 1.3(i))

then, given $k_0 > 0$,

$$\|\chi u\|_{H^1_k(\Omega_+)} \lesssim \|f\|_{L^2(\Omega_+)} \quad (24)$$

for all $k \geq k_0$.

**Proof.** The result for Part (a) is proved in [68, Theorem 7] using the propagation of singularities results of [47], [48]. (See also Vainberg’s book [69] for a broader survey of these methods.) The result for Part (b) was proved when $\Omega_-$ is a nontrapping polygon in [7, Corollary 3]. The bound (24) was proved when $\Omega_-$ is a star-shaped domain in 2- or 3-d in [13, Lemma 3.8].

**Lemma 3.2.** If $w$ satisfies

$$\Delta w + (k^2 + i|k|)w = 0 \quad \text{in } \Omega_+ \quad (25)$$

and the Sommerfeld radiation condition (4) with spectral parameter $\sqrt{k^2 + i|k|}$, then, given $k_0 > 0$,

$$\|w\|^2_{H^1_k(\Omega_+)} \lesssim |k|\|\gamma_+ w\|_{L^2(\Gamma)}\|\partial^+_{\Gamma} w\|_{L^2(\Gamma)} \quad (26)$$

for all $|k| \geq k_0$.

**Proof.** Given $k_0 > 0$, there exists a $c > 0$ such that $\text{Im}\sqrt{k^2 + i|k|} \geq c$; therefore, since $w$ satisfies the Sommerfeld radiation condition and the associated asymptotic expansion (see, e.g., [14, Theorem 3.6]), $w$ decays exponentially at infinity; hence both $w$ and $\nabla w$ are both in $L^2(\Omega_+)$.

We can therefore apply Green’s identity (i.e. multiply the PDE (25) by $\bar{w}$ and integrate by parts), and obtain that

$$-\int_{\Gamma} \frac{\partial_{\Gamma}^+ w}{\gamma_+} \partial_{\Gamma}^+ \bar{w} + \int_{\Omega_+} (k^2 + i|k|)|w|^2 - |\nabla w|^2 = 0.$$

Taking the imaginary part of this last expression and using the Cauchy-Schwarz inequality yields

$$|k|\|w\|^2_{L^2(\Omega_+)} \leq \|\gamma_+ w\|_{L^2(\Gamma)}\|\partial^+_{\Gamma} w\|_{L^2(\Gamma)} \quad (27)$$
Taking the real part yields
\[ \| \nabla w \|_{L^2(\Omega_+)}^2 \leq k^2 \| w \|_{L^2(\Omega_+)}^2 + \| \gamma_+ w \|_{L^2(\Gamma)} \| \partial^+_n w \|_{L^2(\Gamma)}, \]  
and combining (27) and (28) yields the result (26). \[ \square \]

**Lemma 3.3 (Bound on the exterior Dirichlet problem with damping).**

Given \( g_D \in H^1(\Gamma) \), let \( w \) be the solution of
\[ \Delta w + (k^2 + i|k|)w = 0 \quad \text{in } \Omega_+, \quad \gamma_+ w = g_D \quad \text{on } \Gamma, \]
satisfying the Sommerfeld radiation condition (4) (note that the existence of a unique solution to this problem follows from Remark 3.4 below). Then
\[ \| w \|_{H^1(\Omega_+)} \lesssim \| g_D \|_{H^1(\Gamma)}. \]  

**Remark 3.4 (Existence of outgoing solutions to the Dirichlet problem with damping).**

If \( w \) satisfies \( \Delta w + (k^2 + i|k|)w = 0 \), then \( w \) satisfies the Helmholtz equation \( \Delta w + \lambda^2 w = 0 \) with \( \lambda = \sqrt{k^2 + i|k|} \). Since Im \( \lambda > 0 \), the existence of outgoing solutions (i.e. solutions satisfying the Sommerfeld radiation condition (4)) to the Dirichlet and Neumann problems for this equation follows in the same way as in the case Im \( \lambda = 0 \). Indeed uniqueness is proved for Im \( \lambda \geq 0 \) in [14, Theorem 3.13]. Existence in the case Im \( \lambda = 0 \) is proved using integral equation results in [11, Corollary 2.28] (see also [11, Theorem 2.10]), but the proof goes through in exactly the same way when Im \( \lambda > 0 \).

**Proof of Lemma 3.3.** (i) Using the bound (26) in the Nečas result (22) (with \( w = u, f = ikw \)) we find that
\[ \| \partial^+_n w \|_{L^2(\Gamma)}^2 \lesssim \| \nabla (\gamma_+ w) \|_{L^2(\Gamma)}^2 + |k| \| \gamma_+ w \|_{L^2(\Gamma)} \| \partial^+_n w \|_{L^2(\Gamma)}, \]
and so, by using the inequality
\[ 2ab \leq \frac{a^2}{\varepsilon} + \varepsilon b^2, \quad a, b, \varepsilon > 0, \]  
we have
\[ \| \partial^+_n w \|_{L^2(\Gamma)} \lesssim \| \nabla (\gamma_+ w) \|_{L^2(\Gamma)} + |k| \| \gamma_+ w \|_{L^2(\Gamma)}. \]
Using this last expression in (26), we obtain (29). \[ \square \]

**Theorem 3.5 (Bounds on solutions of the Helmholtz Dirichlet problem).**

Given \( g_D \in H^1(\Gamma) \), let \( u \) be the solution of
\[ \Delta u + k^2 u = 0 \quad \text{in } \Omega_+, \quad \gamma_+ u = g_D, \]
satisfying the Sommerfeld radiation condition (4) (with \( \lambda = k \)). If \( \Omega_+ \) satisfies one of the conditions (a), (b), and (c) in Theorem 3.1 then
\[
\| \chi u \|_{H_k^1(\Omega_+)} \lesssim \| g_D \|_{H_k^1(\Gamma)}.
\] (32)

**Proof.** Let \( w \) be as in Lemma 3.3. Let \( \chi \in C_c^\infty(\Omega_+) \) be equal to one in a neighborhood of \( \Omega_- \), and define \( v \) by \( v := u - \chi w \). This definition implies that \( v \in H^1_{bc}(\Omega_+) \) and satisfies the Sommerfeld radiation condition (4) (with \( \lambda = k \)),
\[
\Delta v + k^2 v = h, \quad \text{and} \quad \gamma_+ v = 0,
\]
where
\[
h := ik\chi w - w\Delta \chi - 2\nabla w \cdot \nabla \chi.
\]
Since \( h \) has compact support, the resolvent estimate (24) implies that
\[
\| \chi v \|_{H_k^1(\Omega_+)} \lesssim \| w \|_{H_k^1(\Omega_+)},
\]
and thus
\[
\| \chi u \|_{H_k^1(\Omega_+)} \lesssim \| w \|_{H_k^1(\Omega_+)}.\]
Using the bound (29), we obtain the result (32).

\[\square\]

**Corollary 3.6.** If \( \Omega_+ \) satisfies one of the conditions (a), (b), and (c) in Theorem 3.1 and \( u \) is the outgoing solution to the Dirichlet problem (31) then
\[
\| \partial_+^n u \|_{L^2(\Gamma)} \lesssim \| g_D \|_{H_k^1(\Gamma)}.
\] (33)

**Proof.** This follows from combining the bound (32) with Lemma 2.3.

\[\square\]

**Proof of Theorem 1.4.** The bound (6) is proved in Corollary 3.6 above. The bound (5) then follows by Lemma 2.2.

\[\square\]

4. **Exterior Neumann-to-Dirichlet estimates**

In this section we prove Theorem 1.4, i.e. a bound on the exterior Dirichlet-to-Neumann map for solutions of the Helmholtz equation satisfying the Sommerfeld radiation condition.

This problem is subtler than obtaining bounds on the Dirichlet-to-
Neumann map, since the Neumann boundary condition does not satisfy the uniform Lopatinski condition, hence the classic estimates of Kreiss and Sakamoto do not apply to the wave equation, nor does the simple stationary argument used above for the Dirichlet problem. Indeed, the problem becomes an intrinsically microlocal one, with the degeneracy of the normal derivative at the glancing set making even global energy
estimates extremely sensitive to the boundary geometry (which was irrelevant to energy estimates in the Dirichlet case).

The main technical ingredient in our argument is a collection of estimates proved by Tataru [65] for solutions to the wave equation with Neumann (or indeed many other) boundary conditions, which we now recall. The following is a restatement of part of Theorems 9 of [65].

**Theorem 4.1 (Tataru).** Let $\Gamma$ be smooth. Suppose $v$ satisfies
\begin{align*}
\square v &= 0 \text{ on } \Omega_+ \times [0, T], \\
\partial_n^+ v &= g, \\
v(0) &= v_t(0) = 0.
\end{align*}
Assume $g \in L^2(\Gamma \times [0, T])$. Then
\[ v \in H^\alpha(\Omega_+ \times [0, T]) \]
and
\[ \gamma_+ v \in H^\beta(\Gamma \times [0, T]), \]
where\footnote{The positive curvature used here in dimensions $d = 2, 3$ generalizes to be positive second fundamental form, in general dimension.}
\[ \begin{cases} 
\alpha = 2/3, \quad \beta = 1/3 & \text{in general,} \\
\alpha = 5/6, \quad \beta = 2/3 & \text{if } \Gamma \text{ has strictly positive curvature.}
\end{cases} \quad (35) \]

Other results from [65] that we shall use (Theorems 3, 5) estimate Dirichlet data for solutions of the Helmholtz equation with homogeneous Neumann condition and interior inhomogeneity:

**Theorem 4.2 (Tataru).** Let $\Gamma$ be smooth. Suppose $v \in H^1_{loc}$ satisfies
\begin{align*}
\square v &= F \text{ on } \Omega_+ \times [0, T], \\
\partial_n^+ v &= 0, \\
v(0) &= v_t(0) = 0.
\end{align*}
Assume $F \in L^2(\Omega_+ \times [0, T])$. Then
\[ \gamma_+ v \in H^\alpha(\Gamma \times [0, T]), \]
where $\alpha$ is given by (35).

**Lemma 4.3.** Assume that $\Omega_+$ is nontrapping. Let $R_N(k)$ denote the outgoing Neumann resolvent on $\Omega_+$, acting on $f \in D^s_{N,k}$. Then for $k \gg 0$, for every $s \in \mathbb{R}$
\[ \|\chi R_N(k)\chi f\|_{D^s_{N,k}} \lesssim \|f\|_{D^s_{N,k}} \quad (37) \]
and for $s \in [0, 1]$
\[
\|\gamma R_N(k)\chi f\|_{H^{s+\alpha}_k} \lesssim \|f\|_{\mathcal{D}^s_{N,k}}
\]
(38)

where $\alpha$ is given by (35).

We remark that $2\alpha = 1 + \beta$.

**Proof.** The first part of this estimate is essentially the standard non-trapping resolvent estimate, albeit considered in more general weighted spaces than $L^2$. The second part by contrast requires Tataru’s boundary estimates together with an examination of the details of the Vainberg construction of a parametrix for the nontrapping resolvent [69, Chapter X]. This parametrix is indeed one of the usual routes to obtaining the standard resolvent estimate ((37) with $s = 0$) from the weak Huygens principle (eventual escape of singularities), and depends crucially on propagation of singularities results that enable us to conclude weak Huygens from nontrapping of billiard trajectories. For details, we refer the reader to Theorem 2 in [69], Chapter X; see also [46] and [48] for the geometry and microlocal analysis aspects.

To establish the first part of the result, we recall that Vainberg’s estimate (see also the “black-box” presentation of Vainberg’s method in [64]) yields
\[
\|\chi_1 R_N(k)\chi_2\|_{L^2 \to L^2} \lesssim \langle k \rangle^{-1}.
\]
(39)

We must extend to more general spaces in the domain and range. First, note that if $(\Delta + k^2)u = -f$ and $f$ has compact support in a fixed region and $u$ satisfies the radiation condition then we of course can write, for $\chi_0$ compactly supported,
\[
\|\chi_0 \Delta u\| \leq k^2 \|\chi_0 u\| + \|\chi_0 f\| \lesssim \langle k \rangle \|f\|,
\]
hence for any $\chi$ with smaller support than $\chi_0$,
\[
\|\chi u\|_{\mathcal{D}^s_{N,k}} \lesssim \langle k \rangle \|f\|,
\]
(40)
i.e., in particular
\[
\|\chi R_N(k)\chi\|_{L^2 \to \mathcal{D}^s_{N,k}} \lesssim \langle k \rangle.
\]
(41)
Thus we obtain by interpolating (39) and (41)
\[
\|\chi R_N(k)\chi\|_{L^2 \to \mathcal{D}^1_{N,k}} \lesssim 1.
\]

Now once again if $(\Delta + k^2)u = -f$ then $(\Delta + k^2)(-\Delta + k^2)\ell u = -(-\Delta + k^2)\ell f$, hence
\[
\|\chi_0 (-\Delta + k^2)\ell u\|_{\mathcal{D}^1_{N,k}} \lesssim \|(-\Delta + k^2)\ell f\|,
\]
so that for $\chi$ with smaller support than $\chi_0$ we have

$$\|\chi u\|_{D^2_{N,k}} \lesssim \|f\|_{D^2_{N,k}}.$$ 

Interpolation now yields

$$\|\chi R_N(k)\chi\|_{D^s_{N,k} \to D^{s+1}_{N,k}} \lesssim 1$$

for all $s \geq 0$. Now duality (which exchanges $k$ and $-k$) yields the estimate for $s < 0$ as well. This completes the proof of (37).

To prove (38) we begin by using the Vainberg parametrix construction as presented in [64] to establish the estimate for $s = 0$. In the notation of that paper, we have (see the two displayed equations preceding (3.5))

$$R_N(k)\chi = R^\sharp(k)(I + K(k))^{-1}$$

where $K(k)$ is a holomorphic family of operators that is shown to have small $L^2 \to L^2$ operator norm for $k \gg 0$, so that $(I + K(k))$ is invertible there. The parametrix $R^\sharp(k)$ is defined by

$$R^\sharp(k) = \tilde{R}(k) - \mathcal{F}_{t\to k}((1 - \chi_c)V_a(t))$$

(42)

where $\chi_c = 1$ near $\Omega_-$, and

$$\tilde{R}(k) = -i\mathcal{F}_{t\to k}(\zeta H(t)U(t)\chi).$$

Here $\chi$ (also called $\chi_a$ in [64]) is a cutoff equal to 1 in a neighborhood of $\Omega_-$, $H(t)$ is the Heaviside function,

$$U(t) = \frac{\sin t\sqrt{-\Delta}}{\sqrt{-\Delta}}$$

(sine propagator for the Neumann Laplacian), and $\zeta$ is a cutoff with

$$\zeta(t, z) = \begin{cases} 
1 & t \leq |z| + T_0 \\
0 & t \geq |z| + T_0'
\end{cases}$$

for some $T_0' \geq T_0$. The term $V_a(t)$ is obtained by solving the free wave equation (i.e. with the obstacle removed) with forcing given by the error term $-[\Box, \zeta]U(t)\chi$ and zero Cauchy data. Happily, its analysis will be of no concern here, as the factor $(1 - \chi_c)$ ensures that the corresponding term in (42) vanishes on $\Gamma$.

It thus suffices from (42) to know that $\gamma_+ \tilde{R}(k)$ satisfies the desired estimates. To see this, note that if $f \in L^2$, $\zeta U(t)f$ lies in $L^\infty([0, T]; H^1)$ for each $T < \infty$, simply by the functional calculus for the Neumann Laplacian and the identification of $H^1(\Omega_+)$ with $D^1_{N,k}$. Now Theorems 3 and 5 of [65] imply that

$$\gamma_+ \zeta H(t)U(t)\chi f \in H^\alpha(\mathbb{R} \times \Gamma).$$
(Note that $\zeta$ has compact support in time in a neighborhood of the obstacle, so there is no difference between local and global results here; note also that the factor of $H(t)$ does not affect the regularity since $U(0) = 0$.) We may now Fourier transform this estimate by Lemma 2.1 to get

$$\gamma_+ \tilde{R}(k) f \in H_k^\alpha$$

when $f \in L^2$.

Finally, we extend to more general $s$ in the estimate (38). Fix Fermi normal coordinates near $\Gamma$ with $x$ denoting the normal variable (distance to $\Gamma$) and $y$ denoting coordinates along $\Gamma$. Let $V$ denote any smooth, compactly supported vector field on $\Omega_+$ such that near $\Gamma$, $V$ is of the form $\sum a_j(x,y) \partial_{y_j}$. Then $V$ can be restricted to $\Gamma$ to give a (indeed, any arbitrary) vector field $V_\Gamma$. Note that $[\Delta, V]$ is then a second order differential operator in the $\partial_{y_j}$'s only near $\Gamma$, hence we have (cf. [66, p.407])

$$[\Delta, V] : D^2_{N,k} \to L^2.$$ 

Now if

$$(\Delta + k^2)u = -f \in H^1_\kappa(\Omega_+)$$

with $u$ outgoing and $f$ compactly supported in some fixed set, then we compute

$$V(\Delta + k^2)u = -V f,$$

hence

$$(\Delta + k^2)V u + [V, \Delta] u = -V f.$$ 

Thus, applying the Neumann resolvent and restricting gives

$$V_\Gamma \gamma_+ u = \gamma_+ V u = -\gamma_+ R_N(k)V f - \gamma_+ R_N(k)[V, \Delta] u.$$ 

(43)

Now by the estimate (38) for $s = 0$ obtained above, we have

$$\| \gamma_+ R_N(k)V f \|_{H_k^\alpha} \lesssim \| V f \|_{L^2} \lesssim \| f \|_{H^1_\kappa}.$$ 

Moreover, (37) yields $u \in D^2_{N,k}$ with norm estimated by $\| f \|_{H^1_\kappa}$, hence

$$\| [V, \Delta] u \|_{L^2} \lesssim \| f \|_{H^1_\kappa}.$$ 

Thus, again by the $s = 0$ estimate (38),

$$\| \gamma_+ \gamma_+ R_N(k)[V, \Delta] u \|_{H_k^\alpha} \lesssim \| f \|_{H^1_\kappa},$$

and putting together our estimate for the two terms on the RHS of (43), we have obtained for any vector field $V_\Gamma$ on $\Gamma$,

$$\| V_\Gamma \gamma_+ R_N(k) f \|_{H_k^\alpha} \lesssim \| f \|_{H^1_\kappa}.$$ 

(44)

Also, just the fact that $f \in L^2$ and the $s = 0$ estimate gives

$$\langle k \rangle \| \gamma_+ R_N(k) f \|_{H_k^\alpha} \lesssim \langle k \rangle \| f \|_{L^2} \lesssim \| f \|_{H^1_\kappa}.$$ 

(45)
Since $V_1$ was arbitrary, putting together (44) and (45) yields, for $f$ compactly supported in a fixed set,

$$\|\gamma_+ R_N(k) f\|_{H^1_{k}} \lesssim \|f\|_{H^1_{k}}.$$ 

Interpolating with the $s = 0$ estimate now yields (38) for the whole range $s \in [0, 1]$.

**Theorem 4.4.** Let $\Omega_+$ be nontrapping. For each $\chi \in C_\infty$, there exists $k_0$ so that solutions $u$ of the Helmholtz equation

$$(\Delta + k^2)u = 0 \quad \text{in } \Omega_+$$
$$\partial_n^+ u |_{\Gamma} = g_N$$

satisfying the Sommerfeld radiation condition (4) enjoy the bounds

$$\|\chi u\|_{H^\beta_0(\Omega_+)} \lesssim \|g_N\|_{L^2(\Gamma)}$$

and

$$\|\gamma_+ u\|_{H^\beta_0(\Gamma)} \lesssim \|g_N\|_{L^2(\Gamma)},$$

for $k > k_0$. Here $\alpha$ and $\beta$ are again given by equation (35).

**Proof.** Fix a cutoff function $\varphi(t)$ compactly supported in $(0, 1)$ with $\int \varphi = 1$. Suppose that $v_\kappa$ is the solution of

$$\square v_\kappa = 0,$$
$$\partial_n v_\kappa \bigg|_{\Gamma} = \varphi(t) e^{-i\kappa t} g_N(y) = h_\kappa(t, y),$$
$$v = 0 \quad \text{for } t < 0.$$ 

Note that $\|h_\kappa\|_{L^2(\mathbb{R} \times \Omega_+)} \lesssim \|g_N\|_{L^2(\Gamma)}$ for all $\kappa$; this estimate and all those that follow have implicit constants that are, crucially, uniform in $\kappa$.

Let $I \subset \mathbb{R}$ be an open interval containing supp $\varphi$. By Tataru’s estimates (Theorem 4.1) (and the compact support of $v_\kappa$ on $I \times \Omega_+$) we obtain

$$\|v_\kappa\|_{H^\alpha_0(I \times \Omega_+)} \lesssim \|h_\kappa\|_{L^2(I \times \Gamma)} \lesssim \|g_N\|_{L^2(\Gamma)}.$$ 

We further choose $\psi(t)$ a cutoff function supported in $I$ and equal to 1 on supp $\varphi$. Then we also have

$$\|\psi v_\kappa\|_{H^\alpha_0(\mathbb{R} \times \Omega_+)} \lesssim \|g_N\|_{L^2(\Gamma)}.$$ 

Hence by Lemma 2.1,

$$\|\mathcal{F}^{-1}(\psi v_\kappa)\|_{H^\alpha_0(\Omega_+)} \lesssim \|g_N\|_{L^2(\Gamma)}.$$ 

Now since $v_\kappa$ satisfies the wave equation we have

$$\square (\psi v_\kappa) = [\square, \psi] v_\kappa \in H^{\alpha-1}(\mathbb{R} \times \Omega_+) \subset H^{\alpha-1}(\mathbb{R}; L^2(\Omega_+)).$$
with the norm of the RHS again estimated by a multiple of \(\|g_N\|\). (Note also that \(\psi v_\kappa\) has compact support in \(\Omega_+\).) Hence since \(2\langle k \rangle^{-\alpha+1} L^2(\Omega_+) \subset D_{N,k}^{\alpha-1}(\Omega_+)\) we have

\[
(\Delta + k^2) F^{-1}(\psi v_\kappa) \equiv e_\kappa \in D_{N,k}^{\alpha-1}(\Omega_+),
\]

where

\[
\|e_\kappa\|_{D_{N,k}^{\alpha-1}} \lesssim \|g_N\|.
\]

Now the nontrapping estimates for the Neumann resolvent as stated in Lemma 4.3 tell us that if \(R_N(k)\) denotes the outgoing Neumann resolvent, then for \(k \gg 0\) we have\(^3\)

\[
\|\chi R_N(k)[e_\kappa]\|_{H^\alpha_k} \lesssim \|e_\kappa\|_{H^\alpha_k} \lesssim \|g_N\|.
\]

Now consider

\[
u \equiv F^{-1}(\psi v_\kappa) - R_N(k)[e_\kappa].\]

By the foregoing discussion we have

\[
\|\chi \nu\|_{H^\alpha_k} \lesssim \|g_N\|.
\]

On the other hand, we have

\[
(\Delta + k^2) \nu = 0,
\]

by construction. Moreover, since we used the Neumann resolvent in constructing \(\nu\),

\[
\partial^+_n \nu = \partial^+_n F^{-1}(\psi v_\kappa)
= F^{-1}(\psi(t)\varphi(t)e^{i\kappa t}g_N)
= \hat{\varphi}(k - \kappa)g_N.
\]

Hence if we set \(\kappa = k\) we obtain \(\nu\) as the (unique) solution of (46) satisfying the radiation condition, and have obtained the desired interior estimate.

To derive the boundary estimates, we use Lemma 4.3 as well as Theorem 4.1. The latter implies that

\[
\gamma^+ F^{-1}(\psi v_\kappa) \in H^3_k,
\]

hence by (48) it suffices to consider the term \(R_N(k)[e_\kappa]\). Returning to the definition (47) of \(e_\kappa\) we note that we can in fact write

\[
e_\kappa = F^{-1}(\partial^+_n f^1_\kappa + f^2_\kappa), \text{ where } f^i_\kappa \in H^\alpha_c(I \times \Omega_+).
\]

\(^2\)We are of course using the fact that \(\alpha - 1 < 0\) here.

\(^3\)We are using the identification of Neumann domains and Sobolev spaces for exponents in \([0, 1]\).
Thus we obtain a slightly refined estimate on $e_\kappa$:

$$e_\kappa \in \langle k \rangle H_k^\alpha(\Omega_+).$$

Now since $\alpha \in (0, 1)$, the estimate (38) of Lemma 4.3 yields an estimate on

$$\gamma_+ R_N(k)[e_\kappa] \in \langle k \rangle H_k^{2\alpha}(\Omega_+) \subset H_k^{2\alpha-1}(\Omega_+),$$

as desired. (Recall that $2\alpha - 1 = \beta$.)

**Corollary 4.5.** With notation as above,

$$\|\chi u\|_{H_k^1(\Omega_+)} \lesssim |k|^{1-\alpha} \|g_N\|_{L^2}.$$  

**Proof.** This follows from combining the bounds in Theorem 4.4 with the result of Lemma 2.4.

**Corollary 4.6.** With notation as above, we have

$$\|\gamma_+ u\|_{H_k^1} \lesssim |k|^{-\beta} \|g_N\|_{L^2}.$$  

**Proof.** By the second part of Lemma 2.3, we have

$$\|\gamma_+ u\|_{H_k^1} \lesssim \|g_N\| + |k| \|\gamma_+ u\| + \|\chi R u\|_{H_k^1},$$

hence the results follows from the estimates on the second and third terms given above in Theorem 4.4 and Corollary 4.5 respectively.

**Proof of Theorem 1.5.** The bound (8) follows from combining the bounds in Corollaries 4.5 and 4.6 with Lemma 2.3 (note that $1 - \beta > 1 - \alpha$ in both the general and positive curvature cases). The bound (7) then follows by Lemma 2.2.

5. The interior impedance problem

5.1. Motivation. For readers unfamiliar with the numerical analysis literature on the Helmholtz equation, we explain in this section why the interior impedance problem is of interest to numerical analysts (independent from the fundamental role it plays in the theory of integral equations for exterior problems, which we discuss in §1.3 and §6).

The majority of research effort concerning numerical methods for Helmholtz problems is focused on solving scattering/exterior problems in 2- or 3-d (such as the exterior Dirichlet and Neumann problems considered in §3 and §4). Boundary integral equations (BIEs) are in many ways ideal for this task, since they reduce a $d$-dimensional problem on an unbounded domain to a $(d-1)$-dimensional problem on a bounded domain. However there is still a very large interest in domain-based (as opposed to boundary-based) methods such as the finite element method, partly because these are usually much easier to implement
than BIEs and partly because these domain-based methods usually generalize to the case when $k$ is variable (as occurs, for example, in seismic-imaging applications).

When solving scattering problems with domain-based methods, one must to come to grips with unbounded nature of the domain. This is normally done by truncating the domain: one chooses a (large) bounded domain $\tilde{\Omega} \supset \Omega_-$, imposes a boundary condition on $\partial \tilde{\Omega}$, and then solves the BVP in $\tilde{\Omega} \setminus \Omega_-$. If $\tilde{\Omega}$ is a ball, one can choose the boundary condition on $\partial \tilde{\Omega}$ such that the solution to the BVP in $\tilde{\Omega} \setminus \Omega_-$ is precisely the restriction of the solution to the scattering problem – one does this by using the explicit expression for the solution of the Helmholtz equation in the exterior of a ball, and the relevant boundary condition on $\partial \tilde{\Omega}$ involves the so-called Dirichlet-to-Neumann operator (see, e.g., [34, §3.2] for more details). Alternatively one can impose approximate boundary conditions (often called absorbing boundary conditions or non-reflecting boundary conditions since their goal is to absorb any waves hitting $\partial \tilde{\Omega}$ instead of reflecting them back into $\tilde{\Omega}$), the simplest such one being $\partial u / \partial n - iku = 0$ on $\partial \tilde{\Omega}$. This can be viewed this as an approximation to the radiation condition (4).

Therefore, in the simplest case, truncating a Helmholtz BVP in an unbounded domain yields a BVP for the Helmholtz equation in the annulus-like region $\tilde{\Omega} \setminus \Omega_-$, with an impedance boundary condition on $\partial \tilde{\Omega}$, and either a Dirichlet or Neumann boundary condition on $\Gamma$. Without a $k$-explicit bound on the solution of this BVP, a fully $k$-explicit analysis of any numerical method is impossible, and therefore the problem of finding $k$-explicit bounds on the solution of this truncated problem was considered in [30], [60].

Going one step further, although the geometry of the scatterer plays an important role in determining the behaviour of the solution, many features of numerical methods for the Helmholtz equation (such as whether the so-called pollution effect occurs) can be investigated without the presence of a scatterer at all; this then leads to considering the Helmholtz equation posed in a bounded domain with an impedance boundary condition, i.e. the IIP (and the impedance boundary condition can then be viewed as a way of ensuring that the solution of the BVP is unique for all $k$). The problem of finding $k$-explicit bounds on the solution of the IIP was therefore considered in [23], [44], [15], [21], and [61].

Midway between, in some sense, the truncated scattering problem and the IIP are BVPs posed on bounded domains, where impedance
boundary conditions (or more sophisticated absorbing boundary conditions) are posed on part of the boundary, and Dirichlet or Neumann boundary conditions are posed on the rest. The most commonly-studied such problem is the Helmholtz equation in a rectangle with impedance boundary conditions on one side and Dirichlet boundary conditions on the other three, motivated by the physical problem of scattering by a half plane with a rectangular indent (or “cavity”). Bounds on this problem were obtained in [5] and [39], and the recent paper [17] seeks to determine the optimal dependence on \(k\) via numerical experiments.

5.2. Interior impedance estimates. We now prove Theorem 1.8 by employing the estimates of Bardos–Lebeau–Rauch [6] for the wave equation with the damping boundary condition, i.e.

\[
\Box v = 0 \text{ on } \Omega, \tag{49a}
\]

\[
(\partial_n + a\gamma \partial_t + b\gamma)v = 0 \text{ on } \Gamma \tag{49b}
\]

where \(a, b\) are smooth, real-valued functions on \(\Gamma\) with \(a\) strictly positive and \(b\) nonnegative.

First we give a short proof of the standard energy estimate for the wave equation, but now considering the boundary condition (49) instead of the usual Dirichlet or Neumann ones.

**Lemma 5.1.** Let \(F \in L^2(\mathbb{R} \times \Omega)\) and \(G \in L^2(\mathbb{R} \times \Gamma)\) be supported in \(t > 0\) and let \(v\) solve

\[
\Box v = F \text{ on } \Omega, \tag{50}
\]

\[
(\partial_n + a\gamma \partial_t + b\gamma)v = G \text{ on } \Gamma,
\]

\(v = 0\) for \(t \leq 0\),

where \(a, b\) are smooth, real-valued functions on \(\Gamma\) with \(a\) strictly positive and \(b\) nonnegative. Then for any \(T\)

\[
\|v_t\|^2 + \|\nabla v\|^2 + \|b^{1/2}\gamma v\|^2|_{t=T} \leq C_T\left(\|F\|^2_{L^2([0,T] \times \Omega)} + \|G\|^2_{L^2([0,T] \times \Gamma)}\right).
\]

**Proof.** Without loss of generality we can assume that \(F\) and \(G\) are both real. Multiplying \(\Box v = F\) with \(v_t\) and integrating over \(\Omega\) we find

\[
\frac{\partial}{\partial t} \left( \int_{\Omega} (|\nabla v|^2 + (v_t)^2) + \int_{\Gamma} b(\gamma v)^2 \right) = -\int_{\Gamma} a(\gamma v_t)^2 + \int_{\Gamma} G \gamma v_t + \int_{\Omega} F v_t. \tag{50}
\]

Using both the Cauchy-Schwarz inequality and the inequality (30) on the second term on the right-hand side of (50) and recalling that \(a\) is strictly positive, we see that we can bound the first two terms by a multiple of \(\int_{\Gamma} G^2\). The other term on the right-hand side of (50)
is bounded by \( \frac{1}{2} (\int_{\Omega} F^2 + \int_{\Omega} (v_t)^2) \), and the result then follows from Gronwall’s inequality (see, e.g., [22, §7.2.3]), using the fact that \( b \geq 0 \). □

In the proof of Theorem 1.8 below, the crucial microlocal ingredient will be the estimates on the wave equation with impedance boundary condition obtained by Bardos–Lebeau–Rauch [6]. These estimates involve a key geometric hypothesis, which is that every generalized bicharacteristic in the sense of Melrose–Sjöstrand [48] eventually hits the boundary at a point that is nondiffractive as defined in [6, p.1037].

We claim that in fact these hypotheses are always satisfied for a compact Euclidean domain with smooth boundary.

**Lemma 5.2.** If \( \Omega \subset \mathbb{R}^n \) is a compact domain with smooth boundary, then every generalized bicharacteristic eventually hits the boundary at a nondiffractive point.

**Proof.** We first observe that a generalized bicharacteristic in a compact Euclidean domain must eventually change momentum. Adopting the notation of Hörmander [31, Definition 24.3.7], we claim that the only way the momentum can change along a generalized bicharacteristic is when it hits the boundary at a point in \( \mathcal{H} \cup \mathcal{G} \setminus \mathcal{G}_d \). Here \( \mathcal{H} \) denotes the “hyperbolic points” at which there is transverse reflection from the boundary, while \( \mathcal{G} \setminus \mathcal{G}_d \) denotes the set of glancing points that are not diffractive. To prove this assertion, we note that in the interior and at diffractive points (which together constitute the remaining parts of the characteristic set), we have \( \gamma'(t) = H_p(\gamma(t)) \), where \( \gamma \) denotes the bicharacteristic and \( H_p \) the Hamilton vector field, which in this case is the constant vector field \( \xi \cdot \partial_x \) in \( T^*\mathbb{R}^n \) (cf. Chapter 24 of [31]).

Now we further note that on \( \mathcal{G} \setminus \mathcal{G}_d \), we have \( \gamma'(t) = H_p^G(\gamma(t)) \) with \( H_p^G \) the “gliding vector field” of Definition 24.3.6 in [31]. This vector field still agrees with \( H_p \) unless \( \gamma(t) \in \mathcal{G}_2 \), the points where contact with the boundary is exactly second-order. On the other hand, the “gliding points”, \( \mathcal{G}_g \equiv \mathcal{G}^2 \setminus \mathcal{G}_d \), are nondiffractive by the definition of Bardos–Lebeau–Rauch, since the second derivative of the boundary defining function is strictly negative along the flow at such points (cf. Definition 24.3.2 of [31]). □

**Proof of Theorem 1.8.** We begin by dealing with the case when \( a \) is positive. By [6], if \( v \) satisfies (49) with initial data in the energy space, then all energy norms of \( v \) enjoy exponential decay as \( t \to \infty \). Indeed,

---

\(^4\)Note that the negation of “nondiffractive” in this sense is not the same as “diffractive” in the sense of [48].
[6, Theorem 5.5 and Proposition 5.3] prove this result for the case when $b$ is nonnegative, and then the result for $b \equiv 0$ follows from [6, Theorem 5.6], but we emphasize that in this latter case it is just the energy norm
\[ \|v_t\|^2 + \|\nabla v\|^2 + \|b^{1/2} \gamma v\|^2 \]
that converges to zero, while the value of the solution may converge to a nonzero constant, since this norm does not in general control the $L^2$ norm.

We let $v_\kappa$ denote the (unique) solution to the wave equation on $\mathbb{R} \times \Omega$ satisfying
\begin{align}
\Box v_\kappa &= e^{-i\kappa t} \varphi(t) f, \\
(\partial_n + a \gamma \partial_t + b \gamma) v_\kappa &= e^{-i\kappa t} \varphi(t) g, \\
v_\kappa(t, x) &= 0, \quad t < 0.
\end{align}
where $\varphi$ is a cutoff compactly supported in $(0, 1)$ with $\int \varphi = 1$. Then the standard energy estimate proved in Lemma 5.1 yields
\[ \|v_\kappa\|^2 + \|\nabla v_\kappa\|^2 + \|b^{1/2} \gamma v_\kappa\|^2 \bigg|_{t=1} \lesssim \|f\|^2_{L^2(\Omega)} + \|g\|^2_{L^2(\Gamma)}. \]
Now since $v_\kappa$ satisfies the homogeneous wave equation for $t \geq 1$ with initial data at $t = 1$ controlled as above, [6, Theorem 5.5] yields, for some $\delta > 0$,
\[ \|v_\kappa\|^2 + \|\nabla v_\kappa\|^2 + \|b^{1/2} \gamma v_\kappa\|^2 \leq C e^{-\delta t} \left( \|f\|^2_{L^2(\Omega)} + \|g\|^2_{L^2(\Gamma)} \right), \quad t > 0. \]
(52)
Fourier transforming (51) gives
\begin{align}
(\Delta + k^2) \mathcal{F}^{-1} v_\kappa &= -\hat{\varphi}(k - \kappa) f, \\
(\partial_n - i k \alpha \gamma + b \gamma) \mathcal{F}^{-1} v_\kappa &= \hat{\varphi}(k - \kappa) g.
\end{align}
Since
\[ \|\mathcal{F}^{-1} v\|_{L^2_x} \leq \|v\|_{L^1_t L^2_x} \]
the exponential decay estimate (52) implies that
\[ \|\mathcal{F}^{-1} v_\kappa\|_{H^1_k} \lesssim \|f\| + \|g\|, \quad |k| \geq k_0. \]
If the stronger Assumption 1.7 holds, the more precise version of our Fourier transformed estimates yields
\[ \|\nabla \mathcal{F}^{-1} v_\kappa\|^2 + |k|^2 \|\mathcal{F}^{-1} v_\kappa\|^2 + \|b^{1/2} \gamma \mathcal{F}^{-1} v_\kappa\|^2 \lesssim \|f\| + \|g\|, \quad k \in \mathbb{R}. \]
By the Poincaré inequality, the left side controls the $H^1_k$ norm, even at $k = 0$, giving us the stronger estimate valid on the whole real axis (cf.
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discussion on pps.1060–1061 of [6]):
\[
\| \mathcal{F}^{-1} v_\kappa \|_{H^1_k} \lesssim \| f \| + \| g \|, \ k \in \mathbb{R}.
\]

Taking \( \kappa = k \) makes \( u \equiv v_k \) the solution of the IIP (9) and yields the asserted estimate (10) when \( a \) is strictly positive. This concludes the proof for \( a \) strictly positive. When \( a \) is strictly negative, the sign convention of the Fourier transform and the signs of the exponents in (51) can both be changed to give the correspond estimate. (Alternatively, by taking the complex conjugate of the BVP (9), we can prove (10) when the boundary condition
\[(\partial_n + ik\alpha + b\gamma)u = g\]
is imposed. If \( a \) is strictly negative, then we apply the bound above with \( a \) replaced by \(-a\), and this yields the desired result.) \( \square \)

We now prove Corollary 1.9, regarding the impedance-to-Dirichlet map, by using Theorem 1.8 in conjunction with the result of Nečas. 

**Proof of Corollary 1.9.** A simple argument involving Green’s identity shows that
\[
\| \partial_n u \|_{L^2(\Gamma)} \lesssim \| g \|_{L^2(\Gamma)} \quad \text{and} \quad \| \gamma u \|_{L^2(\Gamma)} \lesssim \frac{1}{|\eta|} \| g \|_{L^2(\Gamma)};
\]
see, e.g., [61, Lemma 4.2]. The \( k \)-explicit result of Nečas written out for exterior domains in Lemma 2.3 also holds for bounded domains (the proof being essentially identical). Using the analogue of the bound (23) with the bounds (9) and (53), we obtain (11). \( \square \)

We now impose the **homogeneous** impedance boundary condition, and consider the operator \((\Delta + k^2)^{-1} : L^2(\Omega) \to L^2(\Omega)\) defined by \((\Delta + k^2)^{-1}f = u\) where \( u \) is the unique solution to \((\Delta + k^2)u = f\) satisfying \((\partial_n - i\eta\gamma)u = 0\).

In order to consider the operator family \((\Delta + k^2)^{-1}\) for \( k \in \mathbb{C} \), we need results about the solvability of the IIP.

**Lemma 5.3 (Uniqueness of the IIP).** Consider the IIP (9) with
\[
\eta(x) = a(x)k + ib(x),
\]
where \( a, b \) are real-valued \( C^\infty \) functions on \( \Gamma \).

(i) If there exists an \( a_- > 0 \) such that
\[
a(x) \geq a_- > 0 \quad \text{for all} \ x \in \Gamma,
\]
and \( b(x) \geq 0 \) on \( \Gamma \), then the solution of the IIP is unique for all \( k \neq 0 \) with \( \text{Im} k \geq 0 \).
(ii) If there exists an \( a_- > 0 \) such that (55) holds and there also exists a \( b_+ > 0 \) such that

\[
b(x) \geq b_+ > 0 \quad \text{for all } x \in \Gamma,
\]

then the solution of the IIP is unique for all \( k \) with \( \text{Im} \, k \geq 0 \) (i.e. we now also have uniqueness when \( k = 0 \)).

Proof. If \( u \) is the solution of the homogeneous IIP (i.e. \( f = 0 \) and \( g = 0 \)) then applying Green’s identity and using the impedance boundary condition we find that

\[
\int_{\Gamma} a |\gamma u|^2 - \int_{\Gamma} b |\gamma u|^2 - \int_{\Omega} |\nabla u|^2 + k^2 \int_{\Omega} |u|^2 = 0.
\]

Therefore, taking real and imaginary parts, and writing \( k = k_R + i k_I \) with \( k_R, k_I \in \mathbb{R} \), we have

\[
- k_I \int_{\Gamma} a |\gamma u|^2 - \int_{\Gamma} b |\gamma u|^2 - \int_{\Omega} |\nabla u|^2 + (k_R^2 - k_I^2) \int_{\Omega} |u|^2 = 0, \quad (57)
\]

and

\[
k_R \int_{\Gamma} a |\gamma u|^2 + 2 k_R k_I \int_{\Omega} |u|^2 = 0 \quad (58)
\]

Proof of (i): if \( k_R \neq 0 \) and \( k_I \geq 0 \), then using the assumption (55) on \( a \) in (58) we see that \( \gamma u = 0 \). The impedance boundary condition then implies that \( \partial_n u = 0 \), and thus Green’s integral representation (see, e.g., [43, Theorem 7.5]) implies that \( u = 0 \) in \( \Omega \). If \( k_R = 0 \) and \( k_I > 0 \), then using the assumption (55) on \( a \) and the assumption that \( b \) is non-negative in (57), we see that \( u = 0 \) in \( \Omega \).

Proof of (ii): from Part (i) we only need to consider the case when \( k = 0 \). Using the assumption (56) in (57), we see that \( \gamma u = 0 \) on \( \Gamma \), and then \( u = 0 \) in \( \Omega \) follows from the steps above. \( \Box \)

Following the discussion in §1, we now proceed with the assumptions that \( a \) and \( b \) are both strictly positive (i.e. (55) and (56) hold), so that the BVP has a unique solution for all \( \text{Im} \, k \geq 0 \).

We break the proof of Theorem 1.10 down into several steps; the first step is to prove that \((\Delta + k^2)^{-1}\) is holomorphic on \( \text{Im} \, k > 0 \).

**Lemma 5.4 (Analyticity for \( \text{Im} \, k > 0 \)).** The operator family \((\Delta + k^2)^{-1} : L^2(\Omega) \to L^2(\Omega)\) with boundary condition

\[
\partial_n u - i(ka + ib)\gamma u = 0, \quad (59)
\]

where \( a, b \) are real-valued \( C^\infty \) functions with a strictly positive on \( \Gamma \) and \( b \) nonnegative, is holomorphic on \( \text{Im} \, k > 0 \).
Proof. First note that the standard variational formulation of the IIP satisfies a Gårding inequality. Indeed, the sesquilinear form is given by

$$a(u, v) = \int_\Omega \nabla u \cdot \nabla \overline{v} - k^2 u \overline{v} - ik \int_\Gamma a \gamma u \overline{\gamma v} + \int_\Gamma b \gamma u \overline{\gamma v},$$

and so, since $b$ is non-negative and $\text{Im} \, k > 0$, we have

$$\text{Re} \, a(v, v) + (1 + k^2) \|v\|^2_{L^2(\Omega)} \geq \|v\|^2_{H^1(\Omega)}$$

(note that we are using the unweighted norm on $H^1(\Omega)$ since we are allowing for $k$ to be equal to zero). Fredholm theory then gives us well-posedness of the BVP as a consequence of the uniqueness result in Lemma 5.3 (see, e.g., [43, Theorems 2.33, 2.34]). Analyticity follows by applying the Cauchy-Riemann operator $\partial / \partial k$ to the equation $(\Delta + k^2)u = f$ and using the uniqueness of the IIP proved above. $\square$

We now use a simple perturbation argument to get the existence of a pole-free strip beneath the real axis.

Proof of Theorem 1.10. Lemma 5.4 states that $(\Delta + k^2)^{-1}$ is holomorphic on $\text{Im} \, k > 0$, while Theorem 1.8 yields the estimate (12) for all $k \in \mathbb{R}$ (crucially using Assumption 1.7). We can now perturb using this estimate to extend to analyticity below the real axis as follows.

For $k \in \mathbb{R}$ and $z \in \mathbb{C}$ we have

$$(\Delta + k^2 + z) = (\Delta + k^2)(I + z(\Delta + k^2)^{-1}),$$

and so

$$(\Delta + k^2 + z)^{-1} = (I + z(\Delta + k^2)^{-1})^{-1}(\Delta + k^2)^{-1}.$$  

Now

$$\|z(\Delta + k^2)^{-1}\|_{L^2 \to L^2} \lesssim |z|(1 + |k|)^{-1}$$

by the arguments above, so there exists a $\delta > 0$ such that if $|z|(1 + |k|)^{-1} < \delta$, then $(\Delta + k^2 + z)^{-1}$ exists with $\|((\Delta + k^2 + z)^{-1} \| \lesssim \|((\Delta + k^2)^{-1} \| \lesssim (1 + |k|)^{-1}$. In particular, then, this estimate holds whenever $z = -\nu^2 - 2ik\nu$ with $|\nu| < \epsilon$ (for some uniform $\epsilon > 0$). Thus we have established our estimates for $(\Delta + k^2 + z)^{-1}$ with $k^2 + z = (k - i\nu)^2$, $|\nu| < \epsilon$, as desired. $\square$

Lemma 5.5 (Sharpness of (10) when $f = 0$ and $\Omega$ is a ball). In $\mathbb{R}^d$ for any $d \geq 2$ there exist families of solutions $u$ to the interior impedance problem in the unit ball $B^d$ with boundary inhomogeneity $g$:

$$\Delta u + k^2 u = 0 \quad \text{in} \, B^d \quad \text{and} \quad \partial_n u - i\eta \gamma u = g \quad \text{on} \, S^{d-1} \quad (60)$$

with

$$k \|u\|_{L^2(B^d)} \gtrsim \|g\|_{L^2(S^{d-1})}.$$
Proof. Fix any spherical harmonic $\varphi(\theta)$ on $S^{d-1}_\theta$ with eigenvalue $-\mu^2$. Then the function

$$u(r, \theta) \equiv r^{1-d/2}J_\nu(kr)\varphi(\theta)$$

solves the Helmholtz equation in $B^d$ if we set

$$\nu = \frac{1}{2}\sqrt{(d-2)^2 + 4\mu^2}.$$

We will let $k \to \infty$ while letting $\mu$ (and hence $\nu$) remain fixed.

The function $u$ thus satisfies the IIP (with $\eta = k$) where

$$g \equiv (-\partial_r - ik)u|_{r=1}.$$

Now we let $k \to \infty$ and examine the asymptotics of $u$ and $g$. Since (see, e.g., [53] for the standard Bessel function asymptotics employed here)

$$u = \varphi(\theta) r^{1-d/2} \sqrt{\frac{2}{kr}} (\cos \omega + O((rk)^{-1}))$$

with

$$\omega \equiv rk - \frac{1}{2}\nu\pi - \frac{1}{4}\pi$$

we have

$$\|u\|_{L^2} \gtrsim k^{-1/2}$$

as $k \to \infty$ with $\nu$ fixed. On the other hand, using the asymptotic expansion of $J'_\nu$ yields

$$\partial_r u = -\varphi(\theta) r^{1-d/2}k \sqrt{\frac{2}{\pi kr}} (\sin \omega + O(k^{-1})),$$

hence at $r = 1$ we have

$$(-\partial_r - ik)u \sim \varphi(\theta) \sqrt{\frac{2k}{\pi}} (-\cos \omega_0 + i\sin \omega_0)$$

with $\omega_0 = k - \frac{1}{2}\nu\pi - \frac{1}{4}\pi$. Thus,

$$\|(-\partial_r - ik)u\|_{L^2(S^{d-1})} \sim Ck^{1/2}.$$

Comparing to (61) yields the desired estimate. \qed
6. Boundary integral equations for the exterior Dirichlet and Neumann problems

In this section we derive both the integral equation (13) for the solution of the exterior Dirichlet problem and the analogous equation for the solution of the exterior Neumann problem. We then give a new proof of the decomposition (14) (which is more intuitive than the proof in [11]), and we then prove an analogous decomposition for the integral equation for the Neumann problem.

We note that there are now many good texts discussing the theory of integral equations for the Helmholtz equation, for example [43], [59], [63], [33]; we will use [11] as a default reference (since it, like us, is concerned with the high-frequency behaviour of these integral operators).

If \( u \) is a solution of the homogeneous Helmholtz equation in \( \Omega_+ \) then

\[
u(x) = -\int_{\Gamma} \Phi_k(x,y) \partial_n^+ u(y) \, ds(y) + \int_{\Gamma} \frac{\partial \Phi_k(x,y)}{\partial n(y)} \gamma_+ u(y) \, ds(y), \quad x \in \Omega_+, \tag{62}\]

(see, e.g., [11, Theorem 2.21]), where \( \Phi_k(x,y) \) is the fundamental solution of the Helmholtz equation given by

\[
\Phi_k(x,y) = \begin{cases} 
\frac{i}{4} H^{(1)}_0(k|x-y|), & d = 2, \\
\Phi_k(x,y) = \frac{e^{ik|x-y|}}{4\pi |x-y|}, & d = 3. 
\end{cases} \tag{63}
\]

Taking the exterior Dirichlet and Neumann traces of (62) on \( \Gamma \) and using the jump relations for the single- and double-layer potentials (see, e.g., [11, Equation 2.41] we obtain the following two integral equations

\[
S_k \partial_n^+ u = \left( -\frac{1}{2} I + D_k \right) \gamma_+ u \tag{64}
\]

and

\[
\left( \frac{1}{2} I + D'_k \right) \partial_n^+ u = H_k \gamma_+ u, \tag{65}
\]

where \( S_k, D_k \) are the single- and double-layer operators, \( D'_k \) is the adjoint double-layer operator, and \( H_k \) is the hypersingular operator. These four integral operators are defined for \( \phi \in L^2(\Gamma), \psi \in H^1(\Gamma), \) and \( x \in \Gamma \) by

\[
S_k \psi(x) := \int_{\Gamma} \Phi_k(x,y) \psi(y) \, ds(y), \quad D_k \phi(x) := \int_{\Gamma} \frac{\partial \Phi_k(x,y)}{\partial n(y)} \phi(y) \, ds(y), \tag{66}
\]

\[
D'_k \psi(x) := \int_{\Gamma} \frac{\partial \Phi_k(x,y)}{\partial n(x)} \psi(y) \, ds(y), \quad H_k \phi(x) := \frac{\partial}{\partial n(x)} \int_{\Gamma} \frac{\partial \Phi_k(x,y)}{\partial n(y)} \phi(y) \, ds(y). \tag{67}
\]
When $\Gamma$ is Lipschitz, the integrals defining $D_k$ and $D'_k$ must be understood as Cauchy principal value integrals and even when $\Gamma$ is smooth there are subtleties in defining $H_k\psi$ for $\psi \in L^2(\Gamma)$ which we ignore here (see, e.g., [11, §2.3]).

6.1. The Dirichlet problem. In the case of the Dirichlet problem, the integral equations (64) and (65) are both integral equations for the unknown Neumann trace $\partial_n^+ u$. However (64) is not uniquely solvable when $-k^2$ is a Dirichlet eigenvalue of the Laplacian in $\Omega_-$, and (65) is not uniquely solvable when $-k^2$ is a Neumann eigenvalue of the Laplacian in $\Omega_-$. (This is because the interior Neumann trace of a solution to the Helmholtz equation satisfies an equation of the form $S_k \partial_n^- u = \ldots$ and the interior Dirichlet trace of a solution to the Helmholtz equation satisfies an equation involving, roughly speaking, the adjoint of $I/2 + D'_k$).

The standard way to resolve this difficulty is to take a linear combination of the two equations, which yields the integral equation

$$A'_{k,\eta} \partial_n^+ u = B_{k,\eta} \gamma_+ u$$

(68)

where

$$A'_{k,\eta} := \frac{1}{2} I + D'_k - i\eta S_k$$

(69)

and

$$B_{k,\eta} := H_k + i\eta \left( \frac{1}{2} I - D_k \right).$$

(70)

If $\eta \in \mathbb{R} \setminus \{0\}$ then the integral operator $A'_{k,\eta}$ is invertible (on appropriate Sobolev spaces) and so (13) can then be used to solve the exterior Dirichlet problem for all (real) $k$. Furthermore one can then show that if $\eta \in \mathbb{R} \setminus \{0\}$ then $A'_{k,\eta}$ is a bounded invertible operator from $H^s(\Gamma)$ to itself for $-1 \leq s \leq 0$; [11, Theorem 2.27].

For the general exterior Dirichlet problem it is natural to pose Dirichlet data in $H^{1/2}(\Gamma)$ (since $\gamma_+ u \in H^{1/2}(\Gamma)$). The mapping properties of $H_k$ and $D_k$ (see [11, Theorems 2.17, 2.18]) imply that $B_{k,\eta} : H^{s+1}(\Gamma) \to H^s(\Gamma)$ for $-1 \leq s \leq 0$, and thus $B_{k,\eta} \gamma_+ u \in H^{-1/2}(\Gamma)$. This indicates that we should consider (68) as an equation in $H^{-1/2}(\Gamma)$.

Unfortunately evaluating the $H^{-1/2}(\Gamma)$ inner product numerically is expensive, and thus it is not practical to implement the Galerkin method on (13) as an equation in $H^{-1/2}(\Gamma)$ (for a short overview of proposed solutions to this problem, see [11, §2.11]). Fortunately, we can bypass this problem in the case of plane-wave or point-source scattering. Indeed, in this case $\gamma_+ u \in H^1(\Gamma)$ and $\partial_n^+ u \in L^2(\Gamma)$ [11, Theorem 2.12]. Since $B_{k,\eta} \gamma_+ u$ and $A'_{k,\eta} \partial_n^+ u$ are then in $L^2(\Gamma)$, we can consider
(68) as an equation in $L^2(\Gamma)$, which is a natural space for implementing the Galerkin method.

6.2. The Neumann problem. In the case of the Neumann problem we can view (68) as an equation to be solved for $\gamma_+ u$. Indeed, given $\partial^+_n u \in H^{-1/2}(\Gamma)$, we have $A'_{k,\eta} \partial^+_n u \in H^{-1/2}(\Gamma)$ and $B_{k,\eta} \gamma_+ u \in H^{-1/2}(\Gamma)$. The equation (68) can then be cast as the variational problem on $H^{1/2}(\Gamma)$: find $\phi \in H^{1/2}(\Gamma)$ such that

$$\langle B_{k,\eta} \phi, \psi \rangle_\Gamma = \langle A'_{k,\eta} \partial^+_n u, \psi \rangle_\Gamma$$

for all $\psi \in H^{1/2}(\Gamma)$, where recall that $\langle \cdot, \cdot \rangle_\Gamma$ is the duality pairing between $H^{-s}(\Gamma)$ and $H^s(\Gamma)$ for $0 \leq s \leq 1$.

Although this gives a practically-realisable Galerkin method, the fact that $B_{k,\eta}$ is a first-kind operator means that the condition number of the discretized system depends on the discretization and thus it is desirable to precondition the equation with an operator of opposite order before discretizing (see, e.g., [63, §13] for a discussion of this technique in general).

For $B_{k,\eta}$ this strategy amounts to multiplying (65) by an operator $R : H^{-1}(\Gamma) \rightarrow L^2(\Gamma)$ and then adding it to $-i \eta$ multiplied by (64). This results in the equation

$$\tilde{B}_{k,\eta} \gamma_+ u = \tilde{A}'_{k,\eta} \partial^+_n u$$

(71)

where

$$\tilde{B}_{k,\eta} := RH_k + i \eta \left( \frac{1}{2} I - D_k \right)$$

and

$$\tilde{A}'_{k,\eta} := R \left( \frac{1}{2} I + D'_k \right) - i \eta S_k.$$ 

The mapping properties of $R$ and the boundary integral operators $S_k, D_k, D'_k, H_k$ imply that both $\tilde{B}_{k,\eta}$ and $\tilde{A}'_{k,\eta}$ are bounded operators mapping $L^2(\Gamma)$ to itself, and thus, in the case when $\partial^+_n u \in L^2(\Gamma)$, (71) can be considered as an integral equation in $L^2(\Gamma)$. Of course, $R$ must satisfy some additional conditions to ensure that (71) has a unique solution for all $k$.

The most common choice is to take $R = S_0$, motivated by the Calderon identity

$$S_0 H_0 = -\frac{1}{2} I + D_0^2$$

([11, Equation 2.56]) and the fact that $S_0(\mathcal{H}_k - H_0)$ is compact (since $\mathcal{H}_k - H_0$ has a weakly singular kernel; see [11, Equation 2.25]).
The choice $R = S_{ik}$ was proposed in [9], and further used and analysed in, e.g., [8], [70]. Other choices for $R$ include principal symbols of certain pseudodifferential operators [8], and (for the indirect analogue of (71)) approximations of the NtD map [2, §8].

6.3. Decompositions of inverses of combined potential operators. The decomposition (14) of $(A'_{k,\eta})^{-1}$ in terms of $P^+_{DtN}$ and $P^{-,\eta}_{ItD}$ is implicit in much of the work on $A'_{k,\eta}$, but was first written down explicitly in [11, Theorem 2.33], along with the analogous decomposition for $B^{-1}_{k,\eta}$ (as a special case of the decomposition of the inverse of the integral operator for the exterior impedance problem).

In Lemma 6.1 below we provide an alternative, more intuitive, proof of these decompositions. We also give the analogous decomposition of the operator $\tilde{B}^{-1}_{k,\eta}$ in terms of $P^+_N$ and $P^{-,\eta,R}_{ItD}$, where the operator $P^{-,\eta,R}_{ItD} : L^2(\Gamma) \to L^2(\Gamma)$ maps $g \in L^2(\Gamma)$ to the Dirichlet trace of the solution of the BVP

$$\Delta u + k^2 u = 0 \quad \text{in } \Omega_-, \quad R\partial_n^- u - i\eta\gamma_- u = g \quad \text{on } \Gamma$$

(assuming appropriate conditions on $R$ are imposed so that this BVP has a unique solution for all $k > 0$).

**Lemma 6.1.** We have the following expressions for the inverses of combined-potential operators:

$$(A'_{k,\eta})^{-1} = I - (P^+_{DtN} - i\eta)P^{-,\eta}_{ItD}, \quad (72)$$

$$(B_{k,\eta})^{-1} = P^+_N - (I - i\eta P^+_N)P^{-,\eta}_{ItD}, \quad (73)$$

$$(\tilde{B}_{k,\eta})^{-1} = P^+_N R^{-1} + (i\eta P^+_N R^{-1} - I)P^{-,\eta,R}_{ItD}. \quad (74)$$

**Proof of Lemma 6.1.** We recall (e.g. from Section 2.5 of [11]) the formula for the interior and exterior Calderón projectors, which project onto pairs of Dirichlet and Neumann data for solutions to the Helmholtz equation in $\Omega_-$ and $\Omega_+$ (with radiation condition) respectively. In terms of layer potentials, we may write these operators as

$$\Pi_\pm = \frac{1}{2} I \pm M_k, \quad M_k \equiv \begin{pmatrix} D_k & -S_k \\ H_k & -D'_k \end{pmatrix}$$

(Here we have departed from the notation of [11] for the Calderón projectors—these authors use $P_\pm$—as the letter $P$ is somewhat overloaded.)

Thus we compute

$$(-i\eta \ 1) \cdot \Pi_- = (-B_{k,\eta} \ A'_{k,\eta}).$$
Hence

\begin{equation}
(-i\eta \ 1) \cdot \Pi_-(\begin{pmatrix} \phi \\ \psi \end{pmatrix}) = g \iff -B_{k,\eta} \phi + A'_{k,\eta} \psi = g. \tag{75}
\end{equation}

On the other hand, since \( \Pi_- \) projects to Cauchy data for the interior Helmholtz problem, we assuredly find that

\begin{equation}
(-i\eta \ 1) \cdot \Pi_-(\begin{pmatrix} \phi \\ \psi \end{pmatrix}) = g \tag{76}
\end{equation}

means that

\( \Pi_-(\begin{pmatrix} \phi \\ \psi \end{pmatrix}) \)

are Cauchy data for the interior impedance problem, hence that we may rewrite

\[ \Pi_-(\begin{pmatrix} \phi \\ \psi \end{pmatrix}) = \begin{pmatrix} P_{\text{ID}}^-(\eta)(g) \\ P_{\text{IN}}^-(\eta)(g) \end{pmatrix}. \]

Since \( \Pi_+ + \Pi_- = I \), we now find that

\[ \Pi_+(\begin{pmatrix} \phi \\ \psi \end{pmatrix}) = \begin{pmatrix} \phi - P_{\text{ID}}^-(\eta)(g) \\ \psi - P_{\text{IN}}^-(\eta)(g) \end{pmatrix}. \]

Note that the RHS is now guaranteed to be Cauchy data for a solution of the exterior Helmholtz equation (with radiation condition) and hence we may write its two components in terms of one another via the maps \( P_{\text{DN}}^+ \) and \( P_{\text{ND}}^+ \).

Now we split into the special cases of \( \phi = 0 \) or \( \psi = 0 \). In the former case we have

\[ \Pi_+(\begin{pmatrix} 0 \\ \psi \end{pmatrix}) = \begin{pmatrix} -P_{\text{ID}}^-(\eta)(g) \\ -P_{\text{DN}}^+(P_{\text{ID}}^-(\eta)(g)) \end{pmatrix}, \]

(where we have written the second component in terms of the first using \( P_{\text{DN}}^+ \)). Thus

\[ \psi = (-i\eta \ 1) \cdot \begin{pmatrix} 0 \\ \psi \end{pmatrix} = (-i\eta \ 1) \cdot (\Pi_+ + \Pi_-) \begin{pmatrix} 0 \\ \psi \end{pmatrix} = (-i\eta \ 1) \cdot \begin{pmatrix} -P_{\text{ID}}^-(\eta)(g) \\ -P_{\text{DN}}^+(P_{\text{ID}}^-(\eta)(g)) \end{pmatrix} + g \]

where we have used (76) to evaluate the \( \Pi_- \) term. Likewise, when \( \psi = 0 \) we have

\[ \Pi_+(\phi) = \begin{pmatrix} \phi - P_{\text{ID}}^-(\eta)(g) \\ P_{\text{DN}}^+(\phi - P_{\text{ID}}^-(\eta)(g)) \end{pmatrix}. \]
Thus
\[
-\imath \eta \phi = (-\imath \eta \ 1) \cdot \begin{pmatrix} \phi \\ 0 \end{pmatrix}
\]
\[
= (-\imath \eta \ 1) \cdot (\Pi_+ + \Pi_-) \begin{pmatrix} \phi \\ 0 \end{pmatrix}
\]
\[
= (-\imath \eta \ 1) \cdot \begin{pmatrix} \phi - P_{\text{RD}}^{-\eta}(g) \\ P_{\text{DN}}^+(\phi - P_{\text{RD}}^{-\eta}(g)) \end{pmatrix} + g
\]

In both cases, solving for \( \psi \) (respectively \( \phi \)) and recalling (75) gives the desired expression in terms of \( g \) (in the latter case, we use that \( \phi = P_{\text{RD}}^+ \circ P_{\text{DN}}^+(\phi) \)).

Finally, to obtain the formula for \( \tilde{B}_{k,\eta} \), we apply the same argument as for \( B_{k,\eta}^{-1} \), but where we consider
\[
(-\imath \eta \ R) \cdot \Pi_-
\]
throughout, rather than
\[
(-\imath \eta \ 1) \cdot \Pi_.
\]

The estimate \( B_{k,\eta}^{-1} \) analogous to the estimate (15) on \( (A'_{k,\eta})^{-1} \) is as follows.

**Lemma 6.2.** Let \( \Omega_+ \subset \mathbb{R}^d \), \( d = 2, 3 \), be a smooth, nontrapping domain and suppose that \( \eta \) satisfies Assumption 1.6. Then, given \( k_0 > 0 \)
\[
\| B_{k,\eta}^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim |k|^{-\beta}
\]
for all \( |k| \geq k_0 \), where \( \beta \) is as in Theorem 1.5.

Since this integral operator is not used in practice, however (as explained in §6.2), we do not include the proof. More generally it appears that
\[
\| B_{k,\eta}^{-1} \|_{L^2(\Gamma) \to H^1(\Gamma)} \lesssim |k|^{1-\beta}
\]
and then an estimate from \( H^{-1/2}(\Gamma) \) to \( H^{1/2}(\Gamma) \) can then be obtained by interpolation.

The decomposition of \( \tilde{B}_{k,\eta}^{-1} \) given by (74) below and the sharp bounds on \( P_{\text{RD}}^+ \) in Theorem 1.5 reduce the problem of bounding \( \| \tilde{B}_{k,\eta}^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)} \) to that of bounding \( P_{\text{RD}}^{-\eta,R} \) for the different choices of \( R \), however we do not pursue this further here.
7. Concluding remarks: the conditioning of $A'_{k,\eta}$

In §1.3 we stated that the present paper combined with the recent work of Galkowski–Smith and Galkowski almost completes the study of the high frequency behaviour of $\|A'_{k,\eta}\|$ and $\| (A'_{k,\eta})^{-1} \|$, and thus of the condition number

$$\text{cond}(A'_{k,\eta}) := \|A'_{k,\eta}\|_{L^2(\Gamma) \to L^2(\Gamma)} \| (A'_{k,\eta})^{-1} \|_{L^2(\Gamma) \to L^2(\Gamma)}.$$  (78)

We conclude this paper by justifying this remark in §7.1, but then also questioning in §7.2 whether the condition number is an appropriate object to study in relation to $A'_{k,\eta}$.

7.1. Upper bounds on $\text{cond}(A'_{k,\eta})$. We begin by recalling the recent sharp bounds on $\|S_k\|_{L^2(\Gamma) \to L^2(\Gamma)}$ and $\|D_k\|_{L^2(\Gamma) \to L^2(\Gamma)}$ proved in [24, Theorem 2], [29, Theorem A.1]. (Note that $\|D_k\|_{L^2(\Gamma) \to L^2(\Gamma)} = \|D'_k\|_{L^2(\Gamma) \to L^2(\Gamma)}$, and so these bounds are sufficient to bound $\|A'_{k,\eta}\|_{L^2(\Gamma) \to L^2(\Gamma)}$.)

**Theorem 7.1.** ([24, Theorem 1.2], [29, Theorem A.1]) With $\Omega_-$ and $\Gamma$ defined in §1.1, if $\Gamma$ is a finite union of compact embedded $C^\infty$ hypersurfaces then there exists $k_0$ such that, for $k \geq k_0$,

$$\|S_k\|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim k^{-1/2} \log k, \quad \|D_k\|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim k^{1/4} \log k.$$  

If $\Gamma$ is a finite union of compact subsets of $C^\infty$ hypersurfaces with strictly positive curvature, then

$$\|S_k\|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim k^{-2/3} \log k, \quad \|D_k\|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim k^{1/6} \log k.$$  

Moreover, modulo the factor $\log k$, all of the estimates are sharp.

(Note that in 2-d the sharp bound $\|S_k\|_{L^2(\Gamma) \to L^2(\Gamma)} \lesssim k^{-1/2}$ was proved in [10, Theorem 3.3].)

Combining these bounds with the bounds on $\|(A'_{k,\eta})^{-1}\|$ (16) and (15), as well as bounds when $\Gamma$ is the circle or sphere obtained by [26], [16], [4] (see the review in [11, §5.4]) we obtain the following theorem.

**Theorem 7.2 (Upper bounds on the condition number).**

(a) If $\Omega_-$ is star-shaped with respect to a ball, $\Gamma$ is piecewise smooth and

$$k^{3/4} \log k \lesssim |\eta| \lesssim k$$

then

$$\text{cond}(A'_{k,\eta}) \lesssim k^{1/2}.$$  (79)

(b) If $\Omega_-$ is nontrapping and $\eta$ satisfies Assumption 1.6 (which includes the case $|\eta| \sim k$), then (79) holds.
(c) If $\Omega_-$ is star-shaped with respect to a ball, $\Gamma$ is the finite union of smooth surfaces with strictly positive curvature, and

$$k^{5/6} \log k \lesssim |\eta| \lesssim k$$

then

$$\text{cond}(A'_{k,\eta}) \lesssim k^{1/3}. \quad (80)$$

In particular, if $\Omega_-$ is a 2- or 3-d ball (i.e. $\Gamma$ is the circle or sphere) then $(80)$ holds when

$$k^{2/3} \lesssim |\eta| \lesssim k$$

and, in particular, $\text{cond}(A'_{k,\eta}) \sim k^{1/3}$ when $|\eta| \sim k$.

Earlier we stated that this theorem “almost completes” the study of $\text{cond}(A'_{k,\eta})$. One thing that is missing is a lower bound on $\text{cond}(A'_{k,\eta})$ that shows the choice $|\eta| \sim k$ is optimal. Indeed, in 2-d, if $\Gamma$ contains a straight line segment, then by [10, Theorem 4.2]

$$\|A'_{k,\eta}\|_{L^2(\Gamma) \to L^2(\Gamma)} \gtrsim \frac{|\eta|}{k^{1/2}} + O\left(\frac{|\eta|}{k}\right) + 1$$

as $k \to \infty$, uniformly in $|\eta|$. The only existing lower bound on $\|(A'_{k,\eta})^{-1}\|$ is $\|(A'_{k,\eta})^{-1}\| \geq 2$, which holds if a part of $\Gamma$ is $C^1$ [10, Lemma 4.1], and with this alone we cannot rule out the possibility that $\text{cond}(A'_{k,\eta}) \ll k^{1/2}$ for a choice of $|\eta| \ll k$ but $|\eta| \gtrsim k^{3/4} \log k$ (although we do not expect this to be the case).

7.2. Should we really be interested in the condition number? To be concrete, we consider solving numerically the integral equation (13) (as an equation in $L^2(\Gamma)$) via the Galerkin method, i.e. given a sequence of finite dimensional nested subspaces $V_N \subset L^2(\Gamma)$, we seek $v_N \in V_N$ such that

$$(A'_{k,\eta}v_N, w_N)_{L^2(\Gamma)} = (f_{k,\eta}, w_N)_{L^2(\Gamma)} \quad \text{for all } w_N \in V_N. \quad (81)$$

We restrict attention to the case when $V_N$ consists of piecewise polynomials (and so we do not consider, e.g., subspaces involving oscillatory basis functions; see, e.g., [11] and the references therein), and furthermore we only consider the $h$-boundary element method (BEM) (i.e. the piecewise polynomials have fixed degree but decreasing mesh width $h$).

Given a basis of $V_N$, equation (81) becomes a system of linear equations; for simplicity we do not consider preconditioning this system.

For the high-frequency numerical analysis of this situation, there are now, roughly speaking, two tasks:
We expect that the subspace dimension \( N \sim h^{-(d-1)} \) must grow with \( k \) in order to maintain accuracy, and we would like \( k \)- and \( \eta \)-explicit bounds on the required growth.

One usually solves the linear system with an iterative solver such as the generalized minimal residual method (GMRES); we expect the number of iterations required to achieve a prescribed accuracy to increase with \( k \), and we would like \( k \)- and \( \eta \)-explicit bounds on this growth.

Regarding 1: The analysis in [27] shows that there exists a \( C > 0 \) such that
\[
h \left( \| D'_k \|_{L^2(\Gamma) \to H^1(\Gamma)} + |\eta| \| S_k \|_{L^2(\Gamma) \to H^1(\Gamma)} \right) \|(A'_{k,\eta})^{-1}\|_{L^2(\Gamma) \to L^2(\Gamma)} \leq C
\]
then the sequence of Galerkin solutions \( v_N \) is quasioptimal (with the constant of quasioptimality independent of \( k \)), i.e.
\[
\| \partial^+_n u - v_N \|_{L^2(\Gamma)} \lesssim \min_{w_N \in V_N} \| \partial^+_n u - w_N \|_{L^2(\Gamma)} ;
\]
see [27, Corollary 4.1]. Therefore, minimizing
\[
\left( \| D'_k \|_{L^2(\Gamma) \to H^1(\Gamma)} + |\eta| \| S_k \|_{L^2(\Gamma) \to H^1(\Gamma)} \right) \|(A'_{k,\eta})^{-1}\|_{L^2(\Gamma) \to L^2(\Gamma)} \quad (82)
\]
gives the least restrictive condition on \( h \).

This is not quite the same as minimizing the condition number, but if we believe that the \( L^2 \to H^1 \)-norms of \( D'_k \) and \( S_k \) are proportional to the \( L^2 \to L^2 \)-norms (with the same constant of proportionality), as they are in the case of the circle and sphere at least (with “constant” of proportionality \( k \)), then minimizing (82) is equivalent to minimizing the condition number.

Two remarks:

- In [27] bounds on the \( L^2 \to H^1 \)-norms are obtained and it is shown that, if \( |\eta| \sim k \) and \( \Omega_- \) is both \( C^2 \) and star-shaped with respect to a ball, then the quantity in (82) is bounded by \( k^{3/2} \) in 2-d, yielding the condition for quasioptimality \( hk^{3/2} \lesssim 1 \). In the case of the circle/sphere, better bounds on the norms can be used to obtain the condition for quasioptimality \( hk^{4/3} \lesssim 1 \). In practice, one sees that the \( h \)-BEM is quasi-optimal when \( hk \lesssim 1 \) (i.e. it does not suffer from the pollution effect), see, e.g., [27, §5], but this observation has yet to be established rigorously.
- Here we have only talked about the \( h \)-BEM; the \( hp \)-BEM (where the polynomial degree, \( p \), is variable) is less senstive to the value of \( \eta \) and the norms of \( A'_{k,\eta} \) and \( (A'_{k,\eta})^{-1} \); see [40], [45] for more details.
Regarding 2: In the discussion above we noted that, in practice, \( hk \lesssim 1 \) is sufficient to ensure \( k \)-independent quasioptimality of the Galerkin method. Since \( N \sim h^{-(d-1)} \), this condition implies that, as \( k \) increases, the size of the linear system must grow like \( k^{(d-1)} \) to maintain accuracy. Iterative methods, such as GMRES, are then the methods of choice for solving such large systems.

For Hermitian matrices there are well-known bounds on the number of iterations of the conjugate gradient method in terms of the condition number of the matrix [28, Chapter 3], and for normal matrices there are well-known bounds on the number of GMRES iterations in terms of the location of the eigenvalues (which can be rewritten in terms of the condition number) [56, Theorem 5], [55, Corollary 6.33] (how satisfactory these bounds are is another question, but they exist). In contrast, for non-normal matrices it is not at all clear that the condition number tells you anything about the behaviour of GMRES (at least, there do not exist any bounds on the number of iterations in terms of the condition number of non-normal matrices).

As a partial illustration of this in the context of Helmholtz integral equations, the recent work of Marburg [41] has emphasized that, at least for certain collocation discretizations of the integral equation (68), used as an integral equation for the Neumann problem, the sign of \( \eta \) affects the number of GMRES iterations (with \( \eta = k \) leading to much smaller iteration counts that \( \eta = -k \)). An analogous effect occurs for similar collocation discretizations of the integral equation (68) used as an equation to solve the Dirichlet problem, with the choice of \( \eta = k \) much better than \( \eta = -k \) [42]. In contrast, the condition number estimates in Theorem 7.2 are independent of the sign of \( \eta \), suggesting that the condition number is not the right tool to investigate the behaviour of GMRES.

A concept that does give bounds on the number of GMRES iterations for non-normal matrices is coercivity. On the operator level (for \( A'_{k,\eta} \) on \( L^2(\Gamma) \)), coercivity is the statement that there exists an \( \alpha_{k,\eta} > 0 \) such that
\[
|(A'_{k,\eta}\phi, \phi)_{L^2(\Gamma)}| \geq \alpha_{k,\eta} \|\phi\|_{L^2(\Gamma)}^2 \quad \text{for all } \phi \in L^2(\Gamma),
\]
and the matrix of the Galerkin method (81) inherits an analogous property (see, e.g., [62, Equation 1.20]). If \( A'_{k,\eta} \) is coercive, then the so-called Elman estimate for GMRES [19], [18, Theorem 3.3], [54, §1.3.2] can be used to prove a bound on the number of GMRES iterations required to achieve a prescribed accuracy, with the bound given in terms of \( \alpha_{k,\eta} \) and \( \|A'_{k,\eta}\|_{L^2(\Gamma) \rightarrow L^2(\Gamma)} \); see [62, Equation 1.21].
It is not clear whether bounds on the number of GMRES iterations obtained via this method are sharp, and so far $A'_{k,\eta}$ has only been proved to be coercive when $\eta \gtrsim k$ and $\Omega_-$ is strictly convex (and under additional smoothness assumptions on $\Gamma$), so we do not yet know enough to make a provably-optimal choice of $\eta$ via this approach. However, we do know that the sign of $\eta$ does matter for coercivity. Indeed, when $\Omega_-$ is a ball, $A'_{k,\eta}$ is coercive when $\eta = k$ [16], but not when $\eta = -k$ [62, §1.2]. The dependence of coercivity on the sign of $\eta$ is consistent, therefore, with the results of Marburg that indicate that the number of GMRES iterations for $A'_{k,\eta}$ depends on the sign of $\eta$.

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References


