

BOUNDARY RIGIDITY AND STABILITY FOR GENERIC SIMPLE METRICS

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1. INTRODUCTION

Let (M, g) be a Riemannian manifold with boundary. Denote by ρ_g the distance function in the metric g . We consider the inverse problem of whether $\rho_g(x, y)$, known for all x, y on ∂M , determines the metric uniquely. This problem arose in geophysics in an attempt to determine the inner structure of the Earth by measuring the travel times of seismic waves. It goes back to Herglotz [H] and Wiechert and Zoeppritz [WZ]. Although the emphasis has been in the case that the medium is isotropic, the anisotropic case has been of interest in geophysics since it has been found that the inner core of the Earth exhibits anisotropic behavior [Cr]. In differential geometry this inverse problem has been studied because of rigidity questions and is known as the boundary rigidity problem. It is clear that one cannot determine the metric uniquely. Any isometry which is the identity at the boundary will give rise to the same measurements. Furthermore, the boundary distance function only takes into account the shortest paths, and it is easy to find counterexamples to unique determination, so one needs to pose some restrictions on the metric. Michel [Mi] conjectured that a *simple* metric g is uniquely determined, up to an action of a diffeomorphism fixing the boundary, by the boundary distance function $\rho_g(x, y)$ known for all x and y on ∂M . We recall

Definition 1.1. We say that the Riemannian metric g is *simple* in M , if ∂M is strictly convex w.r.t. g , and for any $x \in M$, the exponential map $\exp_x : \exp_x^{-1}(M) \rightarrow M$ is a diffeomorphism.

Note that a simple metric g in M can be extended to a simple metric in some M_1 with $M \subset\subset M_1$. If we fix $x = x_0 \in M$ above, we also obtain that each simple manifold is diffeomorphic to a (strictly convex) domain $\Omega \subset \mathbf{R}^n$ with the Euclidean coordinates x in a neighborhood of Ω and a metric $g(x)$ there. For this reason, it is enough to prove our results for domains Ω in \mathbf{R}^n .

Unique recovery of g (up to an action of a diffeomorphism) is known for simple metrics conformal to each other [C1], [B], [Mu1], [Mu2], [MuR], [BG], for flat metrics [Gr] and for simple locally symmetric spaces of negative curvature [BCG]. In two dimensions it was known for simple metrics with negative curvature, [C2] and [O], and recently it was shown in [PU] for simple metrics with no restrictions on the

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curvature. In [SU2], the authors proved this for metrics in a small neighborhood of the Euclidean one. This result was used in [LSU] to prove a semiglobal solvability result.

It is known [Sh1] that a linearization of the boundary rigidity problem near a simple metric g is given by the following integral geometry problem: show that if for a symmetric tensor of order 2, which in coordinates is given by $f = (f_{ij})$, the geodesic X-ray transform

$$I_g f(\gamma) = \int f_{ij}(\gamma(t)) \dot{\gamma}^i(t) \dot{\gamma}^j(t) dt$$

vanishes for all geodesics γ in M , then $f = dv$ for some vector field v with $v|_{\partial M} = 0$, where dv denotes the symmetric differential

$$(1.1) \quad [dv]_{ij} = \frac{1}{2} (\nabla_i v_j + \nabla_j v_i),$$

and $\nabla_k v$ denote the covariant derivatives of the vector field v . We will refer to this property as *s-injectivity* of I_g . More precisely, we have

Definition 1.2. We say that I_g is *s-injective* in M if $I_g f = 0$ and $f \in L^2(M)$ imply $f = dv$ with some vector field $v \in H_0^1(M)$.

On the other hand, it is easy to see that $I_g dv = 0$ for any such v . This is the linear version of the fact that ρ_g does not change on $(\partial M)^2 := \partial M \times \partial M$ under an action of a diffeomorphism as above. The inversion of I_g is a problem of independent interest in integral geometry, and our first two theorems are related to it. S-injectivity of I_g was proved in [PS] for metrics with negative curvature, in [Sh1] for metrics with small curvature and in [ShU] for Riemannian surfaces with no focal points. A conditional and non-sharp stability estimate for metrics with small curvature is also established in [Sh1]. This estimate was used in [CDS] to get local uniqueness results for the boundary rigidity problem under the same condition. In [SU3], we proved stability estimates for s-injective metrics (see (1.2) and Section 2 below) and sharp estimates about the recovery of a 1-form $f = f_j dx^j$ and a function f from the associated $I_g f$. The stability estimates proven in [SU3] were used to prove local uniqueness for the boundary rigidity problem near any simple metric g with s-injective I_g .

Before stating our results we give a definition; see also [Tre].

Definition 1.3. We say that f is analytic in $K \subset \mathbf{R}^n$ (not necessarily open) and denote $f \in \mathcal{A}(K)$ if there exists an open set $U \supset K$ such that f extends analytically in U .

Let Ω be a bounded domain in \mathbf{R}^n , $n \geq 2$ with smooth boundary. We show the following theorem in Section 4.

Theorem 1.4. *Let g be a simple metric in Ω , real analytic in $\bar{\Omega}$. Then I_g is s-injective.*

The proof of Theorem 1.4 is based on the following. For analytic simple metrics, the normal operator $N_g = I_g^* I_g$, where I_g^* denotes the operator adjoint to I_g with respect to an appropriate measure (see Section 2), is an analytic pseudodifferential operator with a non-trivial null space. In Section 3 we construct an analytic parametrix that allows us to reconstruct the solenoidal part of a tensor field from its geodesic X-ray transform, up to a term that is analytic near Ω . If $I_g f = 0$, we

show that for some v vanishing on $\partial\Omega$, $\tilde{f} := f - dv$ must be flat at $\partial\Omega$ and analytic in $\bar{\Omega}$; hence $\tilde{f} = 0$. This is similar to the known argument that an analytic elliptic Ψ DO resolves the analytic singularities, hence cannot have compactly supported functions in its kernel. In our case we have a non-trivial kernel, and complications due to the presence of a boundary, in particular loss of one derivative.

As shown in [SU3], the s -injectivity of I_g for analytic simple g implies a stability estimate for I_g . In the next theorem we show something more, namely that we have a stability estimate for g in a neighborhood of each analytic metric, which leads to stability estimates for generic metrics. The proof is based again on the parametrix construction that reduces the problem to a certain Fredholm type of equation with kernel continuously depending on g , but now g has finite smoothness.

Let $M_1 \supset M$ be a compact manifold which is a neighborhood of M and g extends as a simple metric there. We always assume that our tensors are extended as zero outside M , which may create jumps at ∂M . In (5.1), (5.2), see also [SU3], we define the space that in particular satisfies $H^2(M_1) \subset \tilde{H}^2(M_1) \subset H^1(M_1)$. On the other hand, $f \in H^1(M)$ implies $N_g f \in \tilde{H}^2(M_1)$ despite the possible jump of f at ∂M . It is known that every symmetric tensor $f \in L^2$ can be uniquely decomposed into a solenoidal part f^s , and a potential part dv as above, i.e., $f = f^s + dv$; see Section 2.

Theorem 1.5. *There exists k_0 such that for each $k \geq k_0$, the set $\mathcal{G}^k(M)$ of simple $C^k(M)$ metrics in M for which I_g is s -injective is open and dense in the $C^k(M)$ topology. Moreover, for any $g \in \mathcal{G}^k$,*

$$(1.2) \quad \|f_M^s\|_{L^2(M)} \leq C \|N_g f\|_{\tilde{H}^2(M_1)}, \quad \forall f \in H^1(M),$$

with a constant $C > 0$ that can be chosen locally uniform in \mathcal{G}^k in the $C^k(M)$ topology.

Of course, \mathcal{G}^k includes all real analytic simple metrics in M , according to Theorem 1.4.

The analysis of I_g can also be carried out for symmetric tensors of any order; see e.g. [Sh1]. Since we are motivated by the boundary rigidity problem, and to simplify the exposition, we study only tensors of order 2.

Theorem 1.5 and especially estimate (1.2) allow us to prove in Section 5 the following local generic uniqueness result for the non-linear boundary rigidity problem.

Theorem 1.6. *Let k_0 and $\mathcal{G}^k(M)$ be as in Theorem 1.5. There exists $k \geq k_0$, such that for any $g_0 \in \mathcal{G}^k$, there is $\varepsilon > 0$, such that for any two metrics g_1, g_2 with $\|g_m - g_0\|_{C^k(M)} \leq \varepsilon$, $m = 1, 2$, we have the following:*

$$(1.3) \quad \rho_{g_1} = \rho_{g_2} \text{ on } (\partial M)^2 \text{ implies } g_2 = \psi_* g_1$$

with some $C^{k+1}(M)$ -diffeomorphism $\psi : M \rightarrow M$ fixing the boundary.

We can also formulate the following generic global uniqueness result for simple metrics.

Theorem 1.7. *There exists an open dense set \mathcal{U} of pairs of simple metrics in $C^k(M) \times C^k(M)$, with k as in Theorem 1.6, such that any pair in that set has the property (1.3). Moreover, for any simple $g_1 \in C^k(M)$, the set of simple metrics with the same boundary distance function as g_1 on $(\partial M)^2$ is a complement of a dense open set in the $C^k(M)$ topology.*

Finally, we prove a conditional stability estimate of Hölder type. A similar estimate near the Euclidean metric was proven in [W] based on the approach in [SU2].

Theorem 1.8. *Let k_0 and $\mathcal{G}^k(M)$ be as in Theorem 1.5. Then for any $\mu < 1$, there exists $k \geq k_0$ such that for any $g_0 \in \mathcal{G}^k$, there are $\varepsilon_0 > 0$ and $C > 0$ with the property that for any two metrics g_1, g_2 with $\|g_m - g_0\|_{C(M)} \leq \varepsilon_0$, and $\|g_m\|_{C^k(M)} \leq A$, $m = 1, 2$, with some $A > 0$, we have the following stability estimate:*

$$\|g_2 - \psi_*g_1\|_{C^2(M)} \leq C(A)\|\rho_{g_1} - \rho_{g_2}\|_{C(\partial M \times \partial M)}^\mu$$

with some diffeomorphism $\psi : M \rightarrow M$ fixing the boundary.

One can formulate a global generic stability result in the spirit of Theorem 1.7, with a constant uniform in any compact subset of \mathcal{U} .

A brief outline of the paper is as follows. In Section 3 we construct the analytic parametrix for the normal operator N_g . In Section 4 we prove Theorem 1.4. In Section 5 we use the results of the previous section to prove Theorem 1.5, i.e., generic s -injectivity of I_g . Theorem 1.6 concerning generic uniqueness for the non-linear problem is proved in Section 5. The stability estimate of Theorem 1.8 is proved in Section 7. Even though Theorem 1.8 implies Theorem 1.6, we still include a proof of the latter in Section 6 for convenience of the reader, since it is much shorter.

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2. PRELIMINARIES

We start with some basic facts about symmetric 2-tensors on Riemannian manifolds. For more details, we refer to [Sh1].

As we mentioned in the introduction it is enough to prove the results for the case that the manifold is the closure of a bounded domain with smooth boundary which we will denote by Ω .

Let $g \in C^2(\Omega)$ be a Riemannian metric in Ω . We work with symmetric 2-tensors $f = \{f_{ij}\}$ and with 1-tensors (differential forms) v_j . We use freely the Einstein summation convention and the convention for raising and lowering indices. We think of f_{ij} and $f^{ij} = f_{kl}g^{ki}g^{lj}$ as different representations of the same tensor. If (x, ξ) is a covector, then its components are denoted by x^j , and ξ_j , while ξ^j is defined as $\xi^j = \xi_i g^{ij}$. Next, we denote $|\xi|^2 = \xi_i \xi^i$.

The geodesics of g can also be viewed as the x -projections of the bicharacteristics of the Hamiltonian $H_g(x, \xi) = \frac{1}{2}g^{ij}(x)\xi_i\xi_j$. The energy level $H_g = 1/2$ corresponds to parameterization with arc-length parameter. For any geodesic γ , we have $f_{ij}(\gamma(t))\dot{\gamma}^i(t)\dot{\gamma}^j(t) = f^{ij}(x)\xi_i\xi_j$, where $(x, \xi) = (x(t), \xi(t))$ is the bicharacteristic with x -projection equal to γ .

Set

$$\Gamma_- := \{(x, \omega) \in T^*\Omega; x \in \partial\Omega, |\omega| = 1, \omega_i \nu^i < 0\},$$

where $\nu(x)$ is the outer unit normal to $\partial\Omega$. Introduce the measure

$$d\mu(x, \omega) = |\omega \cdot \nu(x)| dS_x dS_\omega \quad \text{on } \Gamma_-,$$

where dS_x and dS_ω are the surface measures induced by g on $\partial\Omega$ and $\{\omega \in T_x^*\Omega; |\omega| = 1\}$, respectively. If $\partial\Omega$ is given locally by $x^n = 0$, then

$$dS_x = (\det g)^{1/2} dx^1 \dots dx^{n-1} \quad \text{and} \quad dS_\omega = (\det g)^{-1/2} dS_{\omega_0},$$

where dS_{ω_0} is the Euclidean measure on S^{n-1} . Let $(x(t; z, \omega), \xi(t; z, \omega))$ be the bicharacteristic issued from $(z, \omega) \in \Gamma_-$ extended for $t \geq 0$ until the first component reaches $\partial\Omega$ again. Then we set

$$If(z, \omega) = \int f^{ij}(x(t; z, \omega))\xi_i(t; z, \omega)\xi_j(t; z, \omega) dt, \quad (z, \omega) \in \Gamma_-.$$

We will drop the subscript g in I_g unless we have more than one metric and the subscript is needed. By identifying $T\Omega$ with $T^*\Omega$, as explained above, we can think of Γ_- as a subset of $T\Omega$, and then

$$If(x, \theta) = \int f_{ij}(\gamma_{x,\theta}(t))\dot{\gamma}_{x,\theta}^i(t)\dot{\gamma}_{x,\theta}^j(t) dt, \quad (x, \theta) \in \Gamma_-,$$

where $\gamma_{x,\theta}$ is the geodesic issued from x in the direction θ . Since $|\theta| = 1$, t is the arc-length parameter. Clearly, $I : C^\infty(\Omega) \rightarrow L^2(\Gamma_-, d\mu)$. We define the L^2 -space of symmetric tensors $f = \{f_{ij}\}$ with inner product

$$(f, h) = \int_{\Omega} f_{ij}\bar{h}^{ij}(\det g)^{1/2} dx.$$

Similarly, we define the L^2 -space of 1-tensors (vector fields that we identify with 1-forms) and the L^2 -space of functions in Ω . Also, we will work in Sobolev H^s spaces of 2-tensors, 1-forms and functions. In order to keep the notation simple, we will use the same notation L^2 (or H^s) for all those spaces and it will be clear from the context which one we mean.

The map $I : L^2(\Omega) \rightarrow L^2(\Gamma_-, d\mu)$ is bounded [SU3], and therefore the *normal* operator $N := I^*I$ is a well-defined bounded operator in $L^2(\Omega)$. In [SU3], we found that

$$(2.1) \quad [Nf]_{kl}(x) = \frac{2}{\sqrt{\det g}} \int \frac{f^{ij}(y)}{\rho(x, y)^{n-1}} \frac{\partial \rho}{\partial y^i} \frac{\partial \rho}{\partial y^j} \frac{\partial \rho}{\partial x^k} \frac{\partial \rho}{\partial x^l} \det \frac{\partial^2(\rho^2/2)}{\partial x \partial y} dy, \quad x \in \Omega.$$

We always assume that g is extended as a simple metric in a small neighborhood of Ω . Also, we always extend functions or tensors defined in Ω , or similar domains, as 0 outside the domain. Then Nf is well-defined near Ω as well and is independent of small perturbations $\partial\Omega_1$ of $\partial\Omega$, as long as $\Omega_1 \supset \Omega$.

Given a symmetric 2-tensor $f = f_{ij}$, we define the 1-tensor δf called *divergence* of f by

$$[\delta f]_i = g^{jk}\nabla_k f_{ij},$$

where ∇_k are the covariant derivatives of the tensor f . Given a 1-tensor (vector field) v , we denote by dv the 2-tensor known as the symmetric differential of v :

$$[dv]_{ij} = \frac{1}{2}(\nabla_i v_j + \nabla_j v_i).$$

Operators d and $-\delta$ are formally adjoint to each other in $L^2(\Omega)$. It is easy to see that for each smooth v with $v = 0$ on $\partial\Omega$, we have $I(dv) = 0$. This follows from the identity

$$(2.2) \quad \frac{d}{dt} v_i(\gamma(t))\dot{\gamma}^i(t) = [dv(\gamma(t))]_{ij}\dot{\gamma}^i(t)\dot{\gamma}^j(t).$$

It is known that for g smooth enough (see Lemma 2.1 below), each symmetric tensor $f \in L^2(\Omega)$ admits a unique orthogonal decomposition $f = f^s + dv$ into a *solenoidal* tensor $\mathcal{S}f := f^s$ and a *potential* tensor $\mathcal{P}f := dv$, such that both terms are in $L^2(\Omega)$, f^s is solenoidal, i.e., $\delta f^s = 0$ in Ω , and $v \in H_0^1(\Omega)$ (i.e., $v = 0$ on $\partial\Omega$).

In order to construct this decomposition, introduce the operator $\Delta^s = \delta d$ acting on vector fields. This operator is elliptic in Ω , and the Dirichlet problem satisfies the Lopatinskiĭ condition. Denote by Δ_D^s the Dirichlet realization of Δ^s in Ω . Then

$$(2.3) \quad v = (\Delta_D^s)^{-1} \delta f, \quad f^s = f - d(\Delta_D^s)^{-1} \delta f.$$

Notice that even when f is smooth and $f = 0$ on $\partial\Omega$, then f^s does not need to vanish on $\partial\Omega$. To stress the dependence on the domain, when needed, we will use the notation v_Ω and f_Ω^s as well.

Operators \mathcal{S} and \mathcal{P} are orthogonal projectors; see also Lemma 2.1 below. The problem concerning the s-injectivity of I can then be posed as follows: if $If = 0$, show that $f^s = 0$; in other words, show that I is injective on the subspace \mathcal{SL}^2 of solenoidal tensors. Note that $N\mathcal{S} = \mathcal{S}N$, $\mathcal{P}N = N\mathcal{P} = 0$.

In [SU3], we analyzed N . We showed that for simple metrics, it is a Ψ DO of order -1 , as a consequence of (2.1). The operator N is not elliptic; it actually vanishes on $\mathcal{PL}^2(\Omega)$, and its principal symbol $\sigma_p(N)_{ijkl}$ vanishes on the Fourier transforms of locally potential (symmetric) tensors. On the complement of this linear space, however, $\sigma_p(N)$ is elliptic. This allows us to construct a parametrix, and we will use this construction in the next two sections. To obtain f^s modulo smoothing operators, however, requires additional efforts, see Proposition 5.1, because we work in a domain with boundary and f^s is defined by solving a BVP as well; see (2.3). Nevertheless, those arguments allowed us to prove the following a priori stability estimate for the linear problem [SU3] for simple smooth metrics g :

$$(2.4) \quad \|f_\Omega^s\|_{L^2(\Omega)} \leq C\|Nf\|_{\tilde{H}^2(\Omega_1)} + C_t\|f\|_{H^{-t}(\Omega_1)}, \quad \forall f \in H^1(\Omega), \quad \forall t > 0.$$

The norm $\|\cdot\|_{\tilde{H}^2}$ is introduced in (5.2) and $\Omega_1 \supset \Omega$ is a small neighborhood of Ω , where g is still simple. If I is s-injective, then we showed that one can choose $C_t = 0$. Notice that there is a loss of one derivative in (2.4).

In our exposition, we will often use boundary normal (semi-geodesic) coordinates (x', x^n) near a boundary point. They are defined such that $x^n = 0$ defines $\partial\Omega$, $x^n > 0$ in Ω , and $x^n = \rho(x, \partial\Omega)$. The metric g in those coordinates satisfies $g_{in} = \delta_{in}$, and $\Gamma_{nn}^i = \Gamma_{in}^n = 0, \forall i$. We also use the convention that all Greek indices take values from 1 to $n - 1$.

At the end of this section we prove a lemma that justifies the decomposition of a symmetric L^2 -tensor into a solenoidal and a potential part.

Lemma 2.1. *For each $g \in C^1(\bar{\Omega})$, the maps*

$$(\Delta_D^s)^{-1} : H^{-1}(\Omega) \rightarrow H_0^1(\Omega), \quad \mathcal{P}, \mathcal{S} : L^2(\Omega) \longrightarrow L^2(\Omega)$$

are bounded and depend continuously on g .

Proof. We consider $(\Delta_D^s)^{-1}$ first (see also [N, Lemma 4.2], where Δ^s is replaced by $\nabla \cdot \gamma(x)\nabla$ and γ is assumed to be uniformly Lipschitz).

We start with the fact that for a fixed smooth g_0 , $(\Delta_{g_0,D}^s)^{-1}$ is bounded in the spaces above [Ta, p. 307]. Let g_0 and g be two smooth metrics. Then

$$(2.5) \quad (\Delta_{g,D}^s)^{-1} - (\Delta_{g_0,D}^s)^{-1} = (\Delta_{g,D}^s)^{-1} (\Delta_{g_0,D}^s - \Delta_{g,D}^s) (\Delta_{g_0,D}^s)^{-1}.$$

To estimate the difference in the r.h.s. above with the regularity assumptions on g , choose u and v in $H_0^1(\Omega)$. Then

$$\begin{aligned} \left| \langle (\Delta_{g,D}^s - \Delta_{g_0,D}^s)u, v \rangle \right| &= \left| \langle d_{g_0}u, d_{g_0}v \rangle - \langle d_gu, d_gv \rangle \right| \\ &\leq C\|g - g_0\|_{C^1} (\|g\|_{C^1} + \|g_0\|_{C^1}) \|u\|_{H^1} \|v\|_{H^1}. \end{aligned}$$

Let $\|g - g_0\|_{C^1} \leq \varepsilon$. Then for $\varepsilon \ll 1$, $\|g - g_0\|_{C^1} (\|g\|_{C^1} + \|g_0\|_{C^1}) \leq C(g_0)\varepsilon$. As a consequence,

$$\|(\Delta_{g,D}^s)^{-1}\|_{H^{-1} \rightarrow H^1} \leq \|(\Delta_{g_0,D}^s)^{-1}\|_{H^{-1} \rightarrow H^1} \left(1 + C(g_0)\varepsilon \|(\Delta_{g_0,D}^s)^{-1}\|_{H^{-1} \rightarrow H^1} \right).$$

This implies that for $\varepsilon \ll 1$, the l.h.s. above is uniformly bounded by a constant depending on g_0 , i.e.,

$$\|(\Delta_{g,D}^s)^{-1}\|_{H^{-1} \rightarrow H^1} \leq C_1(1 - CC_1\varepsilon)^{-1}, \quad C_1 := \|(\Delta_{g_0,D}^s)^{-1}\|_{H^{-1} \rightarrow H^1}, \quad C := C(g_0).$$

Going back to (2.5), we conclude

$$(2.6) \quad \|(\Delta_{g,D}^s)^{-1} - (\Delta_{g_0,D}^s)^{-1}\|_{H^{-1} \rightarrow H^1} \leq C\|g - g_0\|_{C^1}$$

with C a uniform constant in any small enough C^1 -neighborhood of a fixed g_0 . This inequality allows us to define $(\Delta_{g,D}^s)^{-1} : H^{-1}(\Omega) \rightarrow H_0^1(\Omega)$ for any metric $g \in C^1(\bar{\Omega})$ by approximating with smooth g . Moreover, we get that the resolvent above is continuous in g and (2.6) still holds. As a consequence, \mathcal{S} and \mathcal{P} are also continuous in $g \in C^1$ as operators in $L^2(\Omega)$. This completes the proof of the lemma. \square

Remark also that the lemma above admits the following easy generalization: for $s = 0, 1, \dots$, the resolvent in the lemma also continuously maps H^{s-1} into $H^{s+1} \cap H_0^1$, similarly, \mathcal{P} and \mathcal{S} are bounded in H^s , if $g \in C^k$, $k \gg 1$ (depending on s). Moreover those operators depend continuously on g .

3. THE ANALYTIC PARAMETRIX

In what follows, “analytic” always means real analytic.

Assume that g is a simple analytic metric in $\bar{\Omega}$. Our goal is to reconstruct $f_{\Omega_1}^s$ from Nf up to an analytic-regularizing operator, where Ω_1 is a slightly larger domain. This is the key step towards proving Theorem 1.4 in the next section.

We are going to use the analytic Ψ DO calculus; see [Tre]. Analytic Ψ DO have been used in integral geometry before; see, e.g., [BQ] for uniqueness results for the Euclidean Radon transform with analytic weights.

Next, we will follow the parametrix construction in [SU3] in the new situation, where g is analytic. Since N is not elliptic, we modify it to get an elliptic operator of order -1 first (see also [SU3, sec. 6])

$$(3.1) \quad W = N + N_0\mathcal{P}_{\Omega_2},$$

where N_0 is an analytic Ψ DO with symbol $|\xi|^{-1}$ for $|\xi| > 1$. Recall that $\mathcal{P}_{\Omega_2} = d(\Delta_{\Omega_2,D}^s)^{-1}\delta$. Here $\Omega \subset \Omega_1 \subset \Omega_2$, and Ω_1 is a small strictly convex neighborhood of Ω with analytic boundary, Ω_2 is related to Ω_1 in the same way, and we extend g analytically near Ω_2 . Inside Ω_2 , and therefore, on Ω_1 , the operator W is an elliptic Ψ DO [SU3].

Similarly to [SU3], we have the following lemma.

Lemma 3.1. *There exists $\delta > 0$ such that in $U = \{(x, y) \in \Omega_2 \times \Omega_2; |x - y| < \delta\}$ we have*

$$\begin{aligned} \rho^2(x, y) &= G_{ij}^{(1)}(x, y)(x - y)^i(x - y)^j, \\ \frac{\partial \rho^2(x, y)}{\partial x^j} &= 2G_{ij}^{(2)}(x, y)(x - y)^i, \\ \frac{\partial^2 \rho^2(x, y)}{\partial x^i \partial y^j} &= 2G_{ij}^{(3)}(x, y), \end{aligned}$$

where $G_{ij}^{(1)}, G_{ij}^{(2)}, G_{ij}^{(3)}$ are analytic in U , positively defined, and we have

$$G_{ij}^{(1)}(x, x) = G_{ij}^{(2)}(x, x) = G_{ij}^{(3)}(x, x) = g_{ij}(x).$$

Proof. Let the covector ξ be defined as $\xi = \xi(x, y) = \exp_x^{-1} y$. Then $\xi(x, x) = 0$; therefore

$$(3.2) \quad \xi_i = A_{ij}(x, y)(x^j - y^j) \quad \text{with} \quad A_{ij}(x, y) = \int_0^1 \partial_{y_j} \xi_i(x, x + t(y - x)) dt.$$

The latter is a well-defined analytic function for $x - y$ small enough since then the line segment $[x, y]$ along which we integrate does not leave Ω_2 . For x and y far apart, it may leave Ω_2 , which is geodesically convex but not necessarily convex w.r.t. the Euclidean metric. It is easily seen that $A_{ij}(x, x) = g_{ij}(x)$ and $g^{ij}(x)\xi_i\xi_j = \rho^2(x, y)$, so (3.2) implies the lemma. \square

Proposition 3.2. *N and W are analytic Ψ DOs in Ω_2 .*

Proof. We analyze N first. Recall (2.1). Let V be open such that $V \times V \subset U$, $\text{supp } f \subset V$. Then for $x \in V$,

$$[Nf]_{ij}(x) = \int \check{M}_{ijkl}(x, y, x - y) f^{kl}(y) dy,$$

\check{M} being the inverse Fourier transform of M w.r.t. ξ , where

$$(3.3) \quad \begin{aligned} M_{ijkl}(x, y, \xi) &= 2 \int e^{-i\xi \cdot z} \left(G^{(1)} z \cdot z \right)^{\frac{-n+1}{2}-2} \\ &\times [G^{(2)} z]_i [G^{(2)} z]_j [\check{G}^{(2)} z]_k [\check{G}^{(2)} z]_l \frac{\det G^{(3)}}{\sqrt{\det g}} dz \end{aligned}$$

and $\check{G}_{ij}^{(2)}(x, y) = G_{ij}^{(2)}(y, x)$. It is convenient to make the change $z' = (G^{(1)}(x, y))^{1/2} z$ above to get $M(x, y, \xi) = \check{M}(x, y, (G^{(1)}(x, y))^{-1/2} \xi)$, where

$$(3.4) \quad \begin{aligned} \check{M}_{ijkl}(x, y, \xi) &= 2 \int e^{-i\xi \cdot z} |z|^{-n-3} [G^{(2)}(G^{(1)})^{-1/2} z]_i [G^{(2)}(G^{(1)})^{-1/2} z]_j \\ &\times [\check{G}^{(2)}(G^{(1)})^{-1/2} z]_k [\check{G}^{(2)}(G^{(1)})^{-1/2} z]_l \det(G^{(1)})^{-n/2} \frac{\det G^{(3)}}{\sqrt{\det g}} dz. \end{aligned}$$

As a Fourier transform of a (positively) homogeneous in z distribution, \check{M} is homogeneous in ξ of order -1 . It is an analytic function of all variables for $\xi \neq 0$. To prove this, write

$$\check{M}(x, y, \xi) = \int e^{-i\xi \cdot z} |z|^{-n+1} m(x, y, \theta) dz, \quad \theta = z/|z|$$

and pass to polar coordinates $z = r\theta$. Since m is an even function of θ , we get (see also [H, Theorem 7.1.24])

$$\tilde{M}(x, y, \xi) = \pi \int_{|\theta|=1} m(x, y, \theta) \delta(\theta \cdot \xi) \, d\theta,$$

and our claim follows since m is an analytic function of all its variables in the integral above.

Let $\chi \in C_0^\infty$. We prove first that $\chi(\xi)M_{ijkl}(x, y, \xi)$ is an amplitude of an analytic-regularizing operator for $(x, y) \in U$. Indeed,

$$\begin{aligned} (\chi M)(x, y, D)f &= (2\pi)^{-n} \int \int e^{i(x-y)\cdot\xi} \chi(\xi) M(x, y, \xi) f^{kl}(y) \, dy \, d\xi \\ &= (2\pi)^{-n} \int_{S^{n-1}} \int_0^\infty \int e^{i(x-y)\cdot r\theta} \chi(r\theta) M(x, y, \theta) f^{kl}(y) r^{n-2} \, dy \, dr \, d\theta, \end{aligned}$$

and the analyticity follows from this representation.

Next, $(1 - \chi(\xi))M_{ijkl}(x, y, \xi)$ is an analytic amplitude [Tre, Definition V.2.1-2] for $(x, y) \in U$. The estimates needed to justify this statement follow from the homogeneity of M and the Cauchy integral formula.

The arguments above prove that for any $x_0 \in \Omega_2$, there exists a neighborhood V_{x_0} of x_0 such that M is an analytic amplitude for $(x, y) \in V_{x_0} \times V_{x_0}$; therefore N is an analytic Ψ DO in V_{x_0} . To prove that N is an analytic Ψ DO in the whole Ω_2 , we follow the proof of [Tre, Theorem V.3.4]. The statement follows from the fact that the kernel of N is analytic away from the diagonal, which, combined with what we proved above implies easily that N is analytic pseudo-local in the whole Ω_2 . More precisely, one can define the analytic formal symbol

$$\exp\{\partial_\xi D_y\} M(x, y, \xi)|_{y=x},$$

and this symbol defines an equivalence class of analytic Ψ DOs in a neighborhood of Ω_2 . One can build a true pseudo-analytic symbol $\tilde{a}(x, \xi)$ in Ω_2 based on the formal series above as in [Tre]. For any sufficiently small open set V , one has that $(N - a(x, D))u$ is analytic in Ω_2 for $u \in \mathcal{E}'(V)$, and one can easily extend this to any distribution supported in Ω_2 . This completes the proof for N .

Consider next $(\Delta_{\Omega_2, D}^s)^{-1}$. The operator Δ^s is an analytic elliptic Ψ DO; therefore, it has a parametrix P that is an analytic Ψ DO in Ω_2 , such that $\Delta^s P$ is analytic-regularizing in Ω_2 (we need to work in a bit larger domain in order to cover Ω_2). Let $u = (\Delta_{\Omega_2, D}^s)^{-1}f$. If $\text{supp } f \subset \Omega_2$, then $u - Pf$ solves an equation of the kind (3.5) below with analytic coefficients; therefore, by the interior analytic regularity, $u - Pf$ is analytic in Ω_2 . This shows that $(\Delta_{\Omega_2, D}^s)^{-1}$ equals P up to an analytic-regularizing operator in any compact subset; therefore, $(\Delta_{\Omega_2, D}^s)^{-1}$ is an analytic Ψ DO in Ω_2 .

The remaining operators in (3.1) are clearly analytic Ψ DOs. This completes the proof of Proposition 3.2. □

The next step is to reconstruct $f_{\Omega_1}^s$ from Nf up to an analytic function. We need first a lemma about analyticity up to the boundary of solutions of $\Delta^s v = u$:

Lemma 3.3. *Let $x_0 \in \partial\Omega$, and assume that the metric g and the vector fields u, v_0 are analytic in a (two-sided) neighborhood of x_0 and that $\partial\Omega$ is analytic near x_0 .*

Let the vector field v solve

$$(3.5) \quad \Delta^s v = u \quad \text{in } \Omega, \quad v|_{\partial\Omega} = v_0.$$

Then v extends as an analytic function in some (two-sided) neighborhood of x_0 .

Proof. The lemma follows directly from [MN]. One can first extend v_0 near x_0 as an analytic function and subtract from v a certain function analytic near x_0 that reduces the problem to one with $v_0 = 0$. Next, we observe that the principal symbol of $-\Delta^s$ is a positive matrix for $\xi \neq 0$; hence the system above is strongly elliptic in the terminology of [MN], and the result follows (see also [Tre]). \square

Proposition 3.4. *There exists a bounded operator $P : H^1(\Omega_1) \rightarrow L^2(\Omega_1)$ such that for any symmetric 2-tensor $f \in L^2(\Omega)$ we have*

$$f_{\Omega_1}^s = PNf + Kf,$$

with Kf analytic in $\bar{\Omega}_1$. Moreover, P is an analytic Ψ DO in a neighborhood of Ω_1 of order 1.

Proof. We follow the proof of Theorem 2 in [SU3], where g is smooth only. First, we construct a parametrix L of W in Ω_2 ; see [Tre, Theorem V.3.3]. There exists $L : \mathcal{D}'(\Omega_2) \rightarrow \mathcal{E}'(\Omega_2)$ such that L is an analytic Ψ DO of order 1 in a neighborhood of $\bar{\Omega}_1$, and such that $LW = \text{Id} + K_1$ near $\bar{\Omega}_1$, where $K_1 f \in \mathcal{A}(\bar{\Omega}_1)$ for any $f \in L^2(\Omega_1)$; see [Tre, Remark V.3.3] about composition of analytic Ψ DOs. Then the equality above implies $LW = \text{Id} + K_1$. Apply \mathcal{S}_{Ω_2} to the left and right to get

$$\mathcal{S}_{\Omega_2} L W \mathcal{S}_{\Omega_2} = \mathcal{S}_{\Omega_2} + K_2$$

with K_2 having the property that $K_2 f \in \mathcal{A}(\bar{\Omega}_1)$ for any $f \in L^2(\Omega_1)$. To prove the latter, we use the analytic pseudolocal property of analytic Ψ DOs.

We have $W \mathcal{S}_{\Omega_2} = N$. Therefore, setting $P = \mathcal{S}_{\Omega_2} L$, we get

$$(3.6) \quad PN = \mathcal{S}_{\Omega_2} + K_2 \quad \text{in } \Omega_2.$$

Note that we have showed that K_2 maps $L^2(\Omega_1)$ into $\mathcal{A}(\bar{\Omega}_1)$, but not into $\mathcal{A}(\bar{\Omega}_2)$.

Next, compare $f_{\Omega_1}^s$ and $f_{\Omega_2}^s$ for $f \in L^2(\Omega)$. We have $f_{\Omega_i}^s = f - dv_{\Omega_i}$, where $v_{\Omega_i} = (\Delta_{\Omega_i, D}^s)^{-1} \delta f$, $i = 1, 2$. Thus $f_{\Omega_1}^s = f_{\Omega_2}^s + dw$ in Ω_1 , where the vector field $w = v_{\Omega_2} - v_{\Omega_1} \in H^1(\Omega_1)$ solves

$$(3.7) \quad \Delta^s w = 0 \quad \text{in } \Omega_1, \quad w|_{\partial\Omega_1} = v_{\Omega_2}.$$

Since $\text{supp } f$ is disjoint from $\partial\Omega_1$, we get $v_{\Omega_2} \in \mathcal{A}(\partial\Omega_1)$. By Lemma 3.3, $w \in \mathcal{A}(\bar{\Omega}_1)$; thus $f \mapsto dw|_{\Omega_1}$ is a linear operator mapping $L^2(\Omega)$ into $\mathcal{A}(\bar{\Omega}_1)$. Then the relation

$$f_{\Omega_1}^s = f_{\Omega_2}^s + dw = PNf - K_2 f + dw$$

completes the proof of the proposition. \square

4. S-INJECTIVITY FOR ANALYTIC METRICS; PROOF OF THEOREM 1.4

In this section, we prove Theorem 1.4. We start with a recovery at the boundary result. The next lemma generalizes Lemma 2.3 in [Sh2] by proving that actually $v = 0$ with all derivatives at $\partial\Omega$. On the other hand, in [Sh2], Ω does not need to be convex. Also, the lemma below can be considered as a linear version of Theorem 2.1 in [LSU]: if two metrics have the same boundary distance function, then in boundary normal coordinates, they have the same derivatives of all orders at $\partial\Omega$.

Lemma 4.1. *Let g be a smooth, simple metric in Ω and let f be a smooth symmetric 2-tensor. Assume that $If = 0$. Then there exists a smooth vector field v vanishing on $\partial\Omega$ such that for $\tilde{f} = f - dv$ we have $\partial^m \tilde{f}|_{\partial\Omega} = 0$ for any multiindex m .*

Moreover, if g and f are analytic in a (two-sided) neighborhood of $\partial\Omega$, and $\partial\Omega$ is also analytic, then v can be chosen so that $\tilde{f} = 0$ near $\partial\Omega$.

Proof. We fix $x_0 \in \partial\Omega$ and below we work in some neighborhood of x_0 . Assume that $x = (x', x^n)$ are boundary normal coordinates near x_0 ; therefore there we have $g_{in} = \delta_{in}, \forall i$. We will find a vector field v vanishing on $\partial\Omega$ such that for $\tilde{f} := f - dv$ we have $\tilde{f}_{in} = 0$ for $i = 1, 2, \dots, n$. The latter is equivalent to

$$(4.1) \quad \nabla_n v_i + \nabla_i v_n = 2f_{in}, \quad v|_{x^n=0} = 0, \quad i = 1, \dots, n.$$

Recall that $\nabla_i v_j = \partial_i v_j - \Gamma_{ij}^k v_k$, and that in those coordinates, $\Gamma_{nn}^k = \Gamma_{kn}^n = 0$. We solve (4.1) for $i = n$ first by integration, then $\nabla_n v_n = \partial_n v_n = f_{nn}$; this gives us v_n . Next, we solve the remaining linear system of $n - 1$ equations for $i = 1, \dots, n - 1$, that is, of the form $\nabla_n v_i = 2f_{in} - \nabla_i v_n$, or, equivalently,

$$(4.2) \quad \partial_n v_i - 2\Gamma_{ni}^\alpha v_\alpha = 2f_{in} - \partial_i v_n, \quad v_i|_{x^n=0} = 0, \quad i = 1, \dots, n - 1$$

(recall that $\alpha = 1, \dots, n - 1$). Clearly, if g and f are analytic near $\partial\Omega$, then so is v .

We have $I\tilde{f} = 0$ for (x, ξ) such that $x \in \partial\Omega$ is close to x_0 , $|\xi| = 1$, and its normal component is small enough. This guarantees that the geodesic $\gamma_{x,\xi}$ issued from (x, ξ) hits the boundary again at a point close to x_0 , where $v = 0$. We can adapt the proof of Theorem 2.1 in [LSU] to our situation. For the sake of completeness, we will repeat those arguments. It is enough to prove that

$$(4.3) \quad \partial_n^j \tilde{f}_{\alpha\beta}|_{x=x_0} = 0, \quad \forall j = 0, 1, \dots, \quad \forall \alpha, \beta = 1, \dots, n - 1.$$

Indeed, if (4.3) holds, then we prove (4.3) in the same way for $x \in \partial\Omega$ close to x_0 , so we can differentiate (4.3) w.r.t. x' to get that all derivatives of \tilde{f} on $\partial\Omega$ vanish.

Notice that (4.3) is obvious for $j = 0$. Assume that there is $j \geq 1$ such that (4.3) is not true. The Taylor expansion of \tilde{f} then implies that $\exists \xi_0$ of unit length tangent to $\partial\Omega$ such that $\tilde{f}_{\alpha\beta}(x)\xi^\alpha \xi^\beta$ is either (strictly) positive or negative for $x^n > 0$ and x' both sufficiently small and ξ close to ξ_0 . Notice that in the summation above, we have $\alpha < n$ and $\beta < n$ because $\tilde{f}_{in} = \tilde{f}_{ni} = 0$. Therefore, $I\tilde{f}$ is either (strictly) positive or negative for all $(x, \xi) \in \Gamma_-$ close enough to (x_0, ξ_0) and this is a contradiction.

To make that construction global near $\partial\Omega$, it is enough to note that equation (4.1) is invariant under coordinate changes, so the local construction in fact yields a global one near $\partial\Omega$; see also [Sh2, Lemma 2.2]. Finally, we cut v near $\partial\Omega$ to complete the proof.

If g is analytic up to $\partial\Omega$, then as pointed out above, v is analytic near $\partial\Omega$, up to $\partial\Omega$. Therefore, the same is true for \tilde{f} ; thus $\tilde{f} = 0$ near $\partial\Omega$. \square

Next, we introduce in $\bar{\Omega}$ the global semi-geodesic coordinates that were already used in [SU2], [SU3].

Lemma 4.2. *Let $g \in C^k(\bar{\Omega})$, $k \geq 2$, be a simple metric in Ω . Then there exists a C^{k-1} diffeomorphism $\psi : \Omega \rightarrow \psi(\bar{\Omega})$, such that in the coordinates $y = \psi(x)$, the metric g has the property*

$$(4.4) \quad g_{in} = \delta_{in}, \quad i = 1, \dots, n.$$

Moreover, if $g \in \mathcal{A}(\bar{\Omega})$, then $\psi \in \mathcal{A}(\bar{\Omega})$.

Proof. The proof is essentially given in [SU3] and is based on defining the so-called normal coordinates near a fixed point. Let $\Omega_1 \supset \supset \Omega$ be as above and fix $x_0 \in \partial\Omega_1$. Then $\exp_{x_0}^{-1} : \Omega_1 \rightarrow \exp_{x_0}^{-1}(\Omega_1)$ is a diffeomorphism by our simplicity hypothesis. Choose a Cartesian coordinate system ξ in the tangent space, so that $\xi^n = 0$ is tangent to the boundary of $\exp_{x_0}^{-1}(\Omega_1)$ at $\xi = 0$. Introduce polar coordinates $\xi = r\theta$ in $\exp_{x_0}^{-1}(\Omega_1)$, where $g_{ij}(x_0)\theta^i\theta^j = 1$, $r > 0$. By the strong convexity assumption, θ^n has a positive lower bound in a neighborhood of the closure of $\exp_{x_0}^{-1}(\Omega_1)$, the same is true for r . Then we set $y' = \theta'/\theta_n$, $y_n = r$.

The spheres $r = \text{const.}$ are orthogonal to the geodesics $\theta = \text{const.}$ by the Gauss lemma. Moreover, r is the arc-length along those geodesics. Passing to the y -coordinates, we get that the lines $y' = \text{const.}$ are geodesics orthogonal to the planes $y^n = \text{const.}$, with y^n an arc-length parameter. This proves (4.4).

Clearly, if $g \in \mathcal{A}(\bar{\Omega})$, then the coordinate change above is analytic as well. □

Lemma 4.2 allows us to assume, without loss of generality, that g satisfies (4.4).

Proof of Theorem 1.4. We work in the semi-geodesic coordinates above. Assume that $g \in \mathcal{A}(\bar{\Omega})$, and let $f \in L^2(\Omega)$ be such that $If = 0$. Then, by Proposition 3.4, $f_{\Omega_1}^s \in \mathcal{A}(\bar{\Omega}_1)$. Clearly, $If_{\Omega_1}^s = 0$ as well.

Let v_1 be the v in Lemma 4.1, so that $\tilde{f} := f_{\Omega_1}^s - dv_1$ vanishes near $\partial\Omega_1$. Similarly to (4.1) (but now the coordinates are different), we solve

$$(4.5) \quad \nabla_n v_i + \nabla_i v_n = 2\tilde{f}_{in}, \quad v|_{(\partial\Omega_1)_-} = 0,$$

where $\partial\Omega_{\pm}$ is the set of all boundary points x for which $(x, e_n) \in \Gamma_{\pm}$. As before, we first determine v_n by integrating $\partial_n v_n = \tilde{f}_{nn}$ and taking into account the zero boundary condition. Then $v_n = 0$ in a neighborhood U of $\overline{(\partial\Omega_1)_-}$. Next, we solve the remaining linear system (4.2) along the lines parallel to e_n with boundary conditions as in (4.5). We get that v_i , $i = 1, \dots, n-1$ vanish in U as well. For $f^{\sharp} = f_{\Omega_1}^s - dv_1 - dv$ we then have that $f^{\sharp} = 0$ in U and satisfies $f_{in}^{\sharp} = 0$, $i = 1, \dots, n$. Moreover, $v_1 + v = 0$ on $(\partial\Omega_1)_-$. On the other hand, there is a unique $v^{\sharp} \in C(\bar{\Omega}_1)$ with the property that for $f^{\sharp} := f_{\Omega_1}^s - dv^{\sharp}$ we have $f_{in}^{\sharp} = 0$, $v^{\sharp} = 0$ on $(\partial\Omega_1)_-$, and this v^{\sharp} solves (4.5) with \tilde{f} replaced by $f_{\Omega_1}^s$, so $v^{\sharp} = v_1 + v$. Since all coefficients in the latter system are analytic, and so is $\partial\Omega_1$, we get that v^{\sharp} is analytic in $\bar{\Omega} \setminus \partial(\partial\Omega_1)$, i.e., everywhere in $\bar{\Omega}_1$ with a possible exclusion of the points on $\partial\Omega_1$, where e_n is tangent to $\partial\Omega_1$. The same conclusion therefore holds for f^{\sharp} . On the other hand, $f^{\sharp} = 0$ in U , and U includes a neighborhood of $\partial(\partial\Omega_1)$. By analytic continuation, $f^{\sharp} = 0$ in $\bar{\Omega}_1$.

Thus $f_{\Omega_1}^s = dv^{\sharp}$ in $\bar{\Omega}_1$, and $v^{\sharp} = 0$ on $(\partial\Omega_1)_-$. Since we know that $If_{\Omega_1}^s = 0$, by integrating $f_{\Omega_1}^s = dv^{\sharp}$ along geodesics connecting $(\partial\Omega_1)_-$ and $(\partial\Omega_1)_+$, and using (2.2), we get that $v^{\sharp} = 0$ in $(\partial\Omega_1)_+$ as well, and by continuity, $v^{\sharp} = 0$ on the whole $\partial\Omega_1$. This yields $f_{\Omega_1}^s = 0$. Since $\text{supp } f \subset \bar{\Omega}$, this easily implies (see next proposition) that $\text{supp } v \subset \bar{\Omega}$, as well.

This concludes the proof of Theorem 1.4. □

The following elementary statement was used above and is worth stating separately.

Proposition 4.3. *Let $f = dv$, $v|_{\partial\Omega} = 0$, and $v \in C^1(\bar{\Omega})$. Then $v(y) = 0$ for any y such that $f(y) = 0$, and y can be connected to a point on $\partial\Omega$ by a path that does not intersect $\text{supp } f$.*

Proof. Let y be as above. Then there exists a polygon $p = \gamma_1 \cup \gamma_2 \cup \dots \cup \gamma_m$, each segment $[0, 1] \ni t \mapsto \gamma_j$, $j = 1, \dots, m$ of which is a geodesic, such that p connects some $z \in \partial\Omega$ and y . Integrate (2.2) along γ_1 , using the condition $v|_{\partial\Omega} = 0$, to get $v_i \eta^i = 0$ at $\gamma_1(1)$, where $\eta = \dot{\gamma}_1(1)$ is the velocity vector at the endpoint $\gamma_1(1)$ of γ_1 (different from z). By perturbing the initial point $z = \gamma_1(0)$ of γ_1 a little, and using the simplicity assumption, we get that $v(\gamma_1(1)) = 0$. Similarly, we get that $v = 0$ near $\gamma_1(1)$. Now, we repeat the same argument for γ_2 , etc., until we get $v(y) = 0$. \square

5. GENERIC S-INJECTIVITY OF I ; PROOF OF THEOREM 1.5

In this section, we prove that the set \mathcal{G}^k is open in the $C^k(\bar{\Omega})$ topology for some $k \gg 1$.

First we recall and modify a little some results in [SU3]. We introduce the norm $\|\cdot\|_{\tilde{H}^2(\Omega_1)}$ of Nf in $\Omega_1 \supset \Omega$ in the following way. Choose $\chi \in C_0^\infty$ equal to 1 near $\partial\Omega$ and supported in a small neighborhood of $\partial\Omega$ and let $\chi = \sum_{j=1}^J \chi_j$ be a partition of χ such that for each j , on $\text{supp } \chi_j$ we have coordinates (x_j^i, x_j^n) , with x_j^n a normal coordinate as above. Set

$$(5.1) \quad \|f\|_{\tilde{H}^1}^2 = \int \sum_{j=1}^J \chi_j \left(\sum_{i=1}^{n-1} |\partial_{x_j^i} f|^2 + |x_j^n \partial_{x_j^n} f|^2 + |f|^2 \right) dx,$$

$$(5.2) \quad \|Nf\|_{\tilde{H}^2(\Omega_1)} = \sum_{i=1}^n \|\partial_{x^i} Nf\|_{\tilde{H}^1} + \|Nf\|_{H^1(\Omega_1)}.$$

In other words, in addition to derivatives up to order 1, $\|Nf\|_{\tilde{H}^2(\Omega_1)}$ includes also second derivatives near $\partial\Omega$ but they are realized as first derivatives of ∇Nf tangent to $\partial\Omega$.

The reason for using the $\tilde{H}^2(\Omega_1)$ norm, instead of the stronger $H^2(\Omega_1)$ norm, is that this allows us to work with $f \in H^1(\Omega)$, not only with $f \in H_0^1(\Omega)$, since for such f , extended as 0 outside Ω , we still have that $Nf \in \tilde{H}^2(\Omega_1)$; see [SU3].

The following proposition is a modification of the results in section 6 in [SU3].

Proposition 5.1. *Let $g \in C^k(\bar{\Omega})$ be simple. Then for any $t = 1, 2, \dots$, there exists $k > 0$ and a bounded linear operator*

$$(5.3) \quad Q : \tilde{H}^2(\Omega_1) \longrightarrow \mathcal{S}L^2(\Omega),$$

such that

$$(5.4) \quad QNf = f_\Omega^s + Kf, \quad \forall f \in H^1(\Omega),$$

where $K : H^1(\Omega) \rightarrow \mathcal{S}H^{1+t}(\Omega)$ extends to $K : L^2(\Omega) \rightarrow \mathcal{S}H^t(\Omega)$. If $t = \infty$, then $k = \infty$. Moreover, Q can be constructed so that K depends continuously on g in a small neighborhood of a fixed $g_0 \in C^k(\bar{\Omega})$.

Proof. Here we will work with Ψ DOs with symbols and amplitudes of finite smoothness k with respect to x , y , and ξ (see, e.g., [SU2]) that satisfy a finite number of the seminorm estimates. A Ψ DO of order 0 with such a symbol is bounded in L^2

for $k = 2n + 1$, the composition of two Ψ DOs is a Ψ DO with a similar symbol for $k \gg 1$, and the construction of a parametrix to an elliptic Ψ DO up to a smoothing operator of finite order also requires finitely many steps and derivatives. Similarly, for any m, s , a Ψ DO of order m is bounded locally as an operator mapping H^{s+m} into H^s , provided that its symbol satisfies a finite number of seminorm estimates.

We start with a parametrix of the elliptic operator W ; see (3.1). In contrast to Section 3, it is enough to have the smoothing part K be of finite order only. Moreover, we have to make the construction uniform for g in a small neighborhood of a given g_0 . To this end, we will choose all cut-off functions involved in such a construction independent of g . Observe that it is enough to work with classical Ψ DOs only that have (finite) asymptotic expansions in homogeneous symbols in ξ . For $m > 0$, we construct $B = b(x, D)$ to be such that $b \circ \sigma(\Delta^s) = \text{Id} \pmod{S^{-m}}$ near Ω_1 , and b is constructed with finitely many iterations, as mentioned above. The symbol \circ stands for composition of symbols by means of finite sums, with enough terms to justify the estimate on the remainder. For any $m > 0$ one has $k > 0$, such that the above construction is possible for $g \in C^k$. We construct p_0 such that

$$p_0 \circ (\sigma(N) + |\xi|^{-1} \circ \sigma(d) \circ b \circ \sigma(\delta)) = \text{Id} \pmod{S^{-m}}.$$

The symbol of $S_{\Omega_2} \pmod{S^{-m}}$, can be written as $\Lambda = \text{Id} - \sigma(d) \circ b \circ \sigma(\delta)$. Then

$$p_1 := \Lambda \circ p_0 \circ \Lambda$$

satisfies $p_1 \circ \sigma(N) = \Lambda \pmod{S^{-m}}$ near $\bar{\Omega}_1$. Moreover, the finitely many seminorms needed for the $H^{t+1} \rightarrow H^t$ boundedness of $P_1 := p_1(x, D)$ in any compact in Ω_2 for any fixed t , can be estimated by finitely many seminorms of the symbols involved above, which in turn depends on finitely many derivatives of g .

So we get

$$(5.5) \quad P_1 N f = f - dB\delta f + K_1 f \quad \text{in } \Omega_2, \forall f \in L^2(\Omega),$$

and $K_1 : L^2(\Omega_1) \rightarrow H^t(\Omega_1)$, for any fixed t , if g is smooth enough; moreover K_1 depends continuously on g . As a consequence,

$$(5.6) \quad P_1 N f = f_{\Omega_1}^s + dw + K_1 f \quad \text{in } \Omega_1,$$

where $w = v_{\Omega_1} - B\delta f = (\Delta_{\Omega_1, D}^s)^{-1} \delta f - B\delta f$, and $w|_{\partial\Omega_1} = -B\delta f|_{\partial\Omega_1}$. For any $t > 0$, the map $H^t(\Omega) \ni f \mapsto w|_{\partial\Omega_1} \in H^t(\partial\Omega_1)$ is continuous if g is smooth enough because the kernel of B has any fixed number of continuous derivatives away from the diagonal if g is smooth enough. Moreover, it is continuous in $g \in C^k, k \gg 1$. Since B is a parametrix of Δ^s , for any fixed t , the map $L^2(\Omega) \ni f \mapsto \Delta^s w \in H^t(\Omega_1)$ is bounded, if $k \gg 1$. Considering w as a solution of a Dirichlet problem in Ω_1 , we get that dw in (5.6) belongs to $H^{t+1}(\Omega_1)$; thus we can write (5.6) as

$$(5.7) \quad P_1 N f = f_{\Omega_1}^s + K_2 f \quad \text{in } \Omega_1,$$

where K_2 has the properties of K_1 .

Next, compare f_{Ω}^s and $f_{\Omega_1}^s$. We have $f_{\Omega}^s = f_{\Omega_1}^s + du$ in Ω , where $u = v_{\Omega_1} - v_{\Omega}$. The vector field u solves the BVP

$$(5.8) \quad \Delta^s u = 0 \quad \text{in } \Omega, \quad u|_{\partial\Omega} = v_{\Omega_1}|_{\partial\Omega}.$$

We need to express $v_{\Omega_1}|_{\partial\Omega}$ in terms of Nf . This can be done as follows. By (5.7), and the fact that $f = 0$ outside Ω , one has $-dv_{\Omega_1} = P_1 N f - K_2 f$ in $\Omega_1 \setminus \Omega$. For (x, ξ) in a one-sided neighborhood of $(x_0, \nu(x_0)) \in \Gamma_+$ in $T(\Omega_1 \setminus \Omega)$, where $\nu(x_0)$ is

the outer unit normal to $\partial\Omega$, integrate the above along $\gamma_{x,\xi}$ until this geodesic hits $\partial\Omega_1$, where $v_{\Omega_1} = 0$; denote the corresponding time by $\tau(x, \xi)$. We therefore get

$$[v_{\Omega_1}(x)]_i \xi^i = \int_0^{\tau(x,\xi)} [P_1 N f - K_2 f]_{ij}(\gamma_{x,\xi}(t)) \dot{\gamma}_{x,\xi}^i(t) \dot{\gamma}_{x,\xi}^j(t) dt.$$

Clearly, for any fixed x , a set of n linearly independent ξ 's in any neighborhood of $\nu(x_0)$ is enough to determine $v_{\Omega_1}(x)$. We choose this set independently of x in a neighborhood of each $x_0 \in \partial\Omega$. Then by a compactness argument we choose a finite covering and a finite number of such sets. This allows us to construct an operator P_2 such that

$$(5.9) \quad v_{\Omega_1}|_{\partial\Omega} = P_2(P_1 N - K_2)f.$$

We proved in [SU3] that

$$\|P_2 P_1 h\|_{H^{1/2}(\partial\Omega)} \leq C \|h\|_{\tilde{H}^2(\Omega_1)}, \quad \forall h \in \tilde{H}^2(\Omega_1),$$

and our arguments above also show that $P_2 K_2$ depends continuously on $g \in C^k$, $k \gg 1$.

Let $R : H^{t-\frac{1}{2}}(\partial\Omega) \rightarrow H^t(\Omega)$, be the solution operator $u = Rh$ of the boundary value problem

$$(5.10) \quad \Delta^s u = 0 \quad \text{in } \Omega, \quad u|_{\partial\Omega} = h.$$

Lemma 2.1 and the remark after it imply that R depends continuously on g in the sense of the proposition. Then (5.8) and (5.9) show that $u|_{\Omega} = RP_2(P_1 N - K_2)f$. This and (5.7) yield

$$\begin{aligned} f_{\Omega}^s &= f_{\Omega_1}^s + du = (P_1 N - K_2)f + dRP_2(P_1 N - K_2)f \\ &= (\text{Id} + dRP_2)P_1 N f + K f, \end{aligned}$$

where K has the properties required. To complete the proof, apply \mathcal{S}_{Ω} to the identity above and set $Q = \mathcal{S}_{\Omega}(\text{Id} + dRP_2)P_1$. □

Proof of Theorem 1.5. By Proposition 5.1,

$$QN = S + K.$$

Since $NS = N$, and $SQ = Q$, we get that $K = SKS$. Apply $S + K^*$ to both sides above to get

$$\tilde{Q}N = S + \tilde{K},$$

where $\tilde{Q} = \mathcal{S}(\text{Id} + K^*)Q$, and $\tilde{K} = K^* + K + K^*K$ is self-adjoint and compact in $L^2(\Omega)$, and maps $L^2(\Omega)$ into $\mathcal{S}L^2(\Omega)$. This implies

$$\tilde{Q}N + \mathcal{P} = \text{Id} + \tilde{K} \quad \text{on } L^2(\Omega).$$

Even though a priori we have $\tilde{Q}N : H^1(\Omega) \rightarrow L^2(\Omega)$, the proposition shows that $\tilde{Q}N$ extends to a bounded operator on $L^2(\Omega)$. In what follows, we will indicate the dependence on g by placing the subscript g on N , etc. Note that the norm in L^2 depends on g , too, through the volume form. Assume that I_{g_0} is s-injective (in Ω) for some simple $g_0 \in C^k(\bar{\Omega})$ and, in what follows, assume that g belongs to a small C^k neighborhood of g_0 . Then $N_{g_0} : L^2(\Omega) \rightarrow L^2(\Omega_1)$ is also s-injective. Indeed, assume that $f \in \mathcal{S}L^2(\Omega)$, and $N_{g_0} f = 0$ in Ω_1 . Then $\int_{\Omega} \bar{f} N_{g_0} f dx = \int_{\Gamma_-} |I_{g_0} f|^2 d\mu = 0$; therefore $f = 0$.

On $L^2(\Omega)$, $\text{Id} + \tilde{K}_{g_0}$ has a finite-dimensional kernel \mathcal{F} of solenoidal tensors; let $\{f_1, \dots, f_k\}$ be a basis in it. We can choose the basis such that $\{N_{g_0} f_1, \dots, N_{g_0} f_k\}$

is an orthonormal basis in $N_{g_0}\mathcal{F} \subset L^2(\Omega_1)$ because $N_{g_0} : \mathcal{S}_{g_0}L^2(\Omega) \rightarrow L^2(\Omega_1)$ is injective. We define the finite rank operator $Q_0 : L^2(\Omega_1) \rightarrow L^2(\Omega)$ by setting $Q_0h = \sum_j (h, N_{g_0}f_j)f_j$, where the inner product is in $L^2(\Omega_1)$. Set

$$Q_g^\sharp = \tilde{Q}_g + Q_0.$$

Then

$$(5.11) \quad (Q_g^\sharp N_g + \mathcal{P}_g)f = (\text{Id} + K_g^\sharp)f, \quad \forall f \in L^2(\Omega),$$

with $K_g^\sharp = \tilde{K}_g + Q_0N_g$ compact. We claim that $\text{Id} + K_g^\sharp$ is injective for $g = g_0$. Assume that $(\text{Id} + \tilde{K}_{g_0})f + Q_0N_{g_0}f = 0$. The first term above is orthogonal to \mathcal{F} , and the second one belongs to \mathcal{F} . Therefore, they both vanish, which implies $f \in \mathcal{F}$ and $Q_0N_{g_0}f = 0$. The explicit form of Q_0 yields $(N_{g_0}f, N_{g_0}f_j) = 0, \forall j$, and since f is a linear combination of the f_j 's, we get $f = 0$.

Therefore, $K_{g_0}^\sharp$ is a compact operator on $L^2(\Omega)$ with $\text{Id} + K_{g_0}^\sharp$ injective. This implies that $\text{Id} + K_{g_0}^\sharp$ is actually invertible. Then (5.11) yields the estimate in Theorem 1.5 for $g = g_0$:

$$\|f^s\|_{L^2(\Omega)} \leq C\|N_{g_0}f\|_{\tilde{H}^2(\Omega_1)}, \quad \forall f \in H^1(\Omega).$$

To show that C can be chosen independently of g near $g = g_0$, it is enough to observe that K_g^\sharp , considered as an operator in $L^2(\Omega)$, depends continuously on g for k large enough. Indeed this is true for \tilde{K}_g by Proposition 5.1, and it is also true for N_g in the same space; see for example the representation (3.4). Therefore, for g close enough to g_0 in some C^k topology, $\text{Id} + K_g^\sharp$ remains invertible with a uniform bound on the inverse, i.e., $\|f\| \leq C\|(\text{Id} + K_g^\sharp)f\|$ with some $C > 0$ independent of g . Let $f \in H^1(\Omega)$, and substitute $f = f_{\Omega,g}^s$ in (5.11) to get

$$\begin{aligned} \|f_{\Omega,g}^s\|_{L^2(\Omega)} &\leq C\|Q_g^\sharp N_g f\|_{L^2(\Omega)} \\ &\leq C\left(\|\tilde{Q}_g N_g f\|_{L^2(\Omega)} + \|Q_0 N_g f\|_{L^2(\Omega)}\right) \\ &\leq C'\left(\|N_g f\|_{\tilde{H}^2(\Omega_1)} + \|N_g f\|_{L^2(\Omega_1)}\right) \leq C''\|N_g f\|_{\tilde{H}^2(\Omega_1)}, \quad \forall f \in H^1(\Omega), \end{aligned}$$

with $C'' > 0$ also independent of g in a neighborhood of g_0 . This completes the proof that \mathcal{G}^k is open for some k .

To complete the proof of Theorem 1.5, it is enough to observe that analytic functions are dense in $C^k(\bar{\Omega})$, and if g is close enough to a fixed simple metric g_0 in $C^2(\bar{\Omega})$, then g is also a metric and also simple. \square

6. GENERIC BOUNDARY RIGIDITY; PROOF OF THEOREM 1.6

Since Theorem 1.6 follows from Theorem 1.8, we will only indicate here the slight changes in the proof of Theorem 5 in [SU3] that imply Theorem 1.6. The advantage we have here, compared to [SU3], is that we know that the constant C in (1.2) is locally uniform in g .

We start with a proposition that allows us to think of classes of isometric metrics in C^k , instead of a single metric.

Lemma 6.1. *Let $g, \tilde{g} \in C^k(\bar{\Omega})$, $k \geq 1$, and $\psi : \bar{\Omega} \rightarrow \bar{\Omega}$ be a $C^l(\bar{\Omega})$ diffeomorphism fixing $\partial\Omega$ with $2 \leq l \leq k + 1$. Assume that $\tilde{g} = \psi^*g$. Then $\psi \in C^{k+1}(\bar{\Omega})$, and $\|\psi\|_{C^{k+1}} \leq C(A)$, where A is an upper bound of $\|g\|_{C^k} + \|\tilde{g}\|_{C^k}$.*

Proof. We start with the known formula that relates the Christoffel symbols of g and \tilde{g} :

$$\Gamma_{ij}^m = \frac{\partial x^m}{\partial \psi^s} \frac{\partial \psi^p}{\partial x^i} \frac{\partial \psi^q}{\partial x^j} \tilde{\Gamma}_{pq}^s \circ \psi + \frac{\partial x^m}{\partial \psi^s} \frac{\partial^2 \psi^s}{\partial x^i \partial x^j}.$$

Solve this for $\partial^2 \psi^s / \partial x^i \partial x^j$ to get

$$(6.1) \quad \frac{\partial^2 \psi^m}{\partial x^i \partial x^j} = \frac{\partial \psi^m}{\partial x^s} \Gamma_{ij}^s - \frac{\partial \psi^p}{\partial x^i} \frac{\partial \psi^q}{\partial x^j} \tilde{\Gamma}_{pq}^m \circ \psi.$$

Formula (6.1) was pointed out to the authors by J. Lee. Now, we have $\Gamma_{ij}^m, \tilde{\Gamma}_{ij}^m \in C^{l-1}$, $\nabla \psi \in C^{l-1}$, and therefore $\psi \in C^{l+1}$. Iterating this argument, we get that $\psi \in C^{k+1}$. The estimate in the lemma follows immediately for all derivatives of orders between 2 and $k + 1$ with $C(A)$ that may depend on a bound of $\nabla \psi$ as well. On the other hand, one can easily get $\|\nabla \psi\|_{C^0} \leq C(A)$ by using the formula for ψ^*g . The C^0 -norm of ψ is bounded by assumption, and this completes the proof of the lemma. \square

Let $g_0 \in \mathcal{G}^k$ with k large enough. Let g_1 and g_2 be two metrics such that $\rho_{g_1} = \rho_{g_2}$ on $\partial\Omega \times \partial\Omega$, and

$$(6.2) \quad g_1, g_2 \in \mathcal{B} = \left\{ g \in C^k(\bar{\Omega}); \|g - g_0\|_{C^k(\bar{\Omega})} \leq \varepsilon \right\}.$$

We will show that for $0 < \varepsilon \ll 1$, g_2 is isometric to g_1 .

First, by [LSU], there exists a diffeomorphism ψ fixing the boundary, such that ψ_*g_2 and g_1 coincide at $\partial\Omega$ together with their derivatives up to any fixed order, if $k \gg 1$. The diffeomorphism ψ can be chosen as identifying boundary normal coordinates related to g_1 to those related to g_2 near $\partial\Omega$, and extending this in the whole domain. Then $\psi = \text{Id} + O(\varepsilon)$ in C^{k-2} ; therefore, the modified metric ψ_*g_2 also belongs to \mathcal{B} with k replaced by $k - 3$, and for some $\varepsilon_1 > 0$, such that $\varepsilon_1 \rightarrow 0$, as $\varepsilon \rightarrow 0$. Therefore, we may assume that ψ_*g_2 is still in \mathcal{B} .

Then we pass to semigeodesic coordinates as in Lemma 4.2, related to each metric, i.e., we replace g_1, ψ_*g_2 by their push-forwards $\phi_{1*}g_1, (\phi_2 \circ \psi)_*g_2$ under new diffeomorphisms fixing the boundary. It is important to note that the new metrics still agree at $\partial\Omega$ at any fixed order, if $k \gg 1$ because $\phi_1 = \phi_2$ in $\Omega_1 \setminus \Omega$; see also [SU3]. As above, we can still assume that the new metrics are in \mathcal{B} . This gives us that for $f := \phi_{1*}g_1 - (\phi_2 \circ \psi)_*g_2$ we have

$$(6.3) \quad f \in C^k(\Omega_1), \quad \text{supp } f \subset \bar{\Omega}, \quad f_{in} = 0, \quad i = 1, \dots, n.$$

We now use the fact that the linearization of $\rho_{g_1}(x, y)$ for $(x, y) \in (\partial\Omega)^2$ is $\frac{1}{2}I_{g_1}f(x, \xi)$ [Sh1] with $\xi = \exp_x^{-1}y / \exp_x^{-1}|y|$ to get

$$(6.4) \quad \|N_{g_1}f\|_{L^\infty(\Omega_1)} \leq C\|f\|_{C^1}^2,$$

with C uniform, if $k \geq 2$. Let $\varepsilon > 0$ be such that $\mathcal{B} \subset \mathcal{G}^k$, and the constant C in (1.2) is uniform in \mathcal{B} . Then using (1.2), (6.4), and interpolation estimates, we get that for any $0 < \mu < 1$,

$$\|f^s\|_{L^2} \leq C\|f\|_{L^2}^{1+\mu}$$

with $C > 0$ uniform in \mathcal{B} , if $k = k(\mu) \gg 1$. The final step is to estimate f by f^s . There is no such estimate for general f^s , but we have the advantage here that f

satisfies (6.3). Now, $f_{ni} = 0$ allows us to prove that $\|f\|_{L^2} \leq C\|f^s\|_{H^2}$; see (7.45) and (7.46) in the next section. Using interpolation estimates again, we get

$$\|f\|_{L^2} \leq C\|f\|_{L^2}^{1+\mu}$$

with a new $\mu > 0$. This implies $f = 0$ if $\|f\|_{L^2} \ll 1$, and the latter condition is fulfilled if $\varepsilon \ll 1$. This shows that $g_2 = \phi_*g_1$ with a diffeomorphism ϕ that a priori may have lower regularity than C^{k+1} . Lemma 6.1 shows that in fact, $\phi \in C^{k+1}$.

This concludes the sketch of the proof of Theorem 1.6.

Proof of Theorem 1.7. Fix k as in Theorem 1.6. The identity $g_2 = \psi^*g_1$, with ψ as in (1.3), is an equivalence relation; for k fixed, see Lemma 6.1. Let us denote that relation by $g_1 \sim g_2$. We define \mathcal{U} as follows: it consists of all pairs (g_1, g_2) of simple C^k metrics such that $g_1 \not\sim g_2$ and g_1, g_2 have distinct distance functions on the boundary plus all $(g_1, g_2) \in \mathcal{G}^k(\Omega) \times \mathcal{G}^k(\Omega)$ with $g_1 \sim g_2$. We will show first that \mathcal{U} is open in $C^k \times C^k$. Fix $(g_1, g_2) \in \mathcal{U}$. Assume first that $g_1 \not\sim g_2$. Since the pair is in \mathcal{U} , we have that $\rho_{g_1} \neq \rho_{g_2}$ on $(\partial\Omega)^2$. Since $C^k(\bar{\Omega}) \ni g \mapsto \rho_g^2 \in C((\partial\Omega)^2)$ is a continuous map, it follows that a small perturbation of (g_1, g_2) will keep the distance functions distinct. Now, assume that $g_1 \sim g_2$, i.e., $\psi^*g_2 = g_1$, and let \tilde{g}_1, \tilde{g}_2 be ε -perturbations of g_1, g_2 in C^k . Then $\psi^*\tilde{g}_2$ is an $O(\varepsilon)$ perturbation of $\psi^*g_2 = g_1$ in C^k ; see Lemma 6.1. We can apply Theorem 1.6 to $g_0 := g_1$, and $\tilde{g}_1, \psi_*\tilde{g}_2$ (playing the roles of g_1 and g_2) to conclude that for $0 < \varepsilon \ll 1$, $\tilde{g}_1, \psi_*\tilde{g}_2$ are either isometric metrics, both in $\mathcal{G}^k(\Omega)$, or they have distinct boundary distance functions, i.e., $(\tilde{g}_1, \psi_*\tilde{g}_2) \in \mathcal{U}$. This implies the same for $(\tilde{g}_1, \tilde{g}_2)$. Therefore, \mathcal{U} is open.

To prove that \mathcal{U} is dense, observe that any pair (g_1, g_2) of real analytic simple metrics belongs to \mathcal{U} . This is true for $g_1 \not\sim g_2$ by the fact that an analytic simple metric is uniquely determined by its boundary distance function; see [LSU]. It is also true when $g_1 \sim g_2$ by Theorem 1.4.

To prove the last statement of Theorem 1.7, fix a simple C^k metric g . Let g_2 also be a simple C^k metric with distinct boundary distance function (then $g \not\sim g_2$). A small perturbation of g_2 will preserve this property, as shown above. To prove the density statement, fix a simple C^k metric g_3 , and $\varepsilon > 0$. If g_3 has a distinct boundary distance function from that of g , we are done. If it is the same, choose $g_4 \in \mathcal{G}^k$, at a distance from g_3 not exceeding $\varepsilon/2$. Again, if g_4 has a distinct boundary distance function from that of g , we are done. Otherwise, if $\varepsilon \ll 1$, some $\varepsilon/2$ perturbation g_5 of g_4 (actually, any that is not equivalent to g_4) would necessarily change the boundary distance function of the latter by Theorem 1.6. Therefore, there is a metric at distance at most ε from g_2 with a different boundary distance function from that of g . \square

7. STABILITY FOR THE NON-LINEAR PROBLEM

In this section, we give a proof of the stability estimate in Theorem 1.8. Since the proof is rather technical, we will sketch the main point below.

In section 7.1, we first prove stability of recovery of all derivatives of g (in boundary normal coordinates), which is also of independent interest; see Theorem 7.1 below. As one may expect, the information about the derivatives of g at $\partial\Omega$ is hidden in the derivatives of $\rho_g(x, y)$ at $x = y \in \partial\Omega$ but that relationship is hard to follow and an attempt to express $\partial^\alpha g|_{\partial\Omega}$ in terms of the derivatives of $\rho_g(x, y)$ through a recursive procedure leads to significant technical difficulties. Instead, we

“linearize” the problem by reducing it essentially to one for the linearized problem for a family of metrics; see (7.1).

In Section 7.2, we complete the proof by showing stability in the interior, using essentially the stability at the boundary established in Section 7.1. We basically follow the uniqueness proof given in Section 6 by showing that each step is actually stable. We start with two metrics g and \tilde{g} with δ -close distance functions, see (7.15), and in a series of steps we transform them by actions of diffeomorphisms, and by $O(\delta^\mu)$ perturbations into pairs (g_j, \tilde{g}_j) , $j = 1, 2, 3, 4$. The goal is to get g_4, \tilde{g}_4 that coincide in an $O(\delta^\mu)$ neighborhood of $\partial\Omega$, and satisfy $g_{in} = \delta_{in}, \tilde{g}_{in} = \delta_{in} + O(\delta^\mu), \forall i$, making it possible to apply the stability estimate for the linearized problem (1.2). We start with boundary normal coordinates and pass to global semigeodesic coordinates.

7.1. Stability at the boundary. As explained above, we start with a theorem about stability at the boundary for the non-linear problem. It was first shown by R. Michel [Mi] that the boundary distance function determines all derivatives of g at $\partial\Omega$ in 2 dimensions. In $n \geq 3$ dimensions this was done in [LSU], while the second author and Wang [UW] gave a constructive procedure.

Given two metrics g_0 and g_1 , in a fixed coordinate system, there is a diffeomorphism ψ near $\partial\Omega$ fixing $\partial\Omega$, and mapping the geodesics for g_0 normal to $\partial\Omega$ into geodesics for g_1 normal to $\partial\Omega$, by preserving the arc-length. Such a diffeomorphism is defined by means of boundary normal coordinates for each metric and can be extended to a global diffeomorphism. Then g_0 and ψ_*g_1 have common normal geodesics to $\partial\Omega$, close to $\partial\Omega$, and moreover, if (x', x^n) are boundary normal coordinates near a fixed boundary point for one of those metrics, they are also boundary normal coordinates for the other metric.

Theorem 7.1. *Let g_0 and g_1 be two simple metrics in Ω , and $\Gamma \subset\subset \Gamma' \subset \partial\Omega$ be two sufficiently small open subsets of the boundary. Let ψ be as above. Then*

$$\|\partial_{x^n}^k(\psi_*g_1 - g_0)\|_{C^m(\bar{\Gamma})} \leq C_{k,m} \|\rho_{g_1}^2 - \rho_{g_0}^2\|_{C^{m+2k+2}(\overline{\Gamma' \times \Gamma'})},$$

where $C_{k,m}$ depends only on Ω and on an upper bound of g_0, g_1 in $C^{m+2k+5}(\bar{\Omega})$.

Proof. In this proof, we will denote $\psi_{1*}g_1$ by g_1 ; thus the normal coordinates (x', x^n) related to g_0 are also normal coordinates for g_1 . It is enough to prove the theorem for Γ a small neighborhood of a fixed $x_0 \in \partial\Omega$, and we are going to use boundary normal coordinates there. For any $x = (x', 0)$ close to $(x'_0, 0)$, set $y = (x' + \varepsilon p', 0)$, where $\frac{1}{2} \leq |p'| \leq 2$, and $\varepsilon \geq 0$ is a small parameter. Set

$$\tilde{\rho}_{g_s}(\varepsilon; x', p') = \rho_{g_s}(x, y), \quad s = 0, 1.$$

With some abuse of notation, we will drop the tilde below. Denote

$$\|f\|_m = \|f\|_{C^m(\bar{\Gamma})}, \quad \|\rho_{g_1}^2 - \rho_{g_0}^2\|_m = \sup_{|\alpha|+l \leq m, x' \in \Gamma', \frac{1}{2} \leq |p'| \leq 2} \left| \partial_\varepsilon^l \Big|_{\varepsilon=0} \partial_{x'}^\alpha (\rho_{g_1}^2 - \rho_{g_0}^2) \right|.$$

If $[0, 1] \ni t \rightarrow \gamma_s(t)$ is the geodesic in the metric g_s connecting x and y , with t a natural parameter, then

$$\rho_{g_s}^2(\varepsilon; x', p') = \int_0^1 g_{s,ij}(\gamma_s) \dot{\gamma}_s^i \dot{\gamma}_s^j dt,$$

and, moreover, γ_s minimizes the r.h.s. above.

The following step is crucial in this proof. We replace $s \in \{0, 1\}$ by a continuous parameter s by setting $g_s = (1 - s)g_0 + sg_1$, $0 \leq s \leq 1$. We show below that $\partial\Omega$ is strictly convex w.r.t. each g_s . Then

$$(7.1) \quad \begin{aligned} \rho_{g_1}^2(\varepsilon; x', p') - \rho_{g_0}^2(\varepsilon; x', p') &= \int_0^1 \frac{d}{ds} \int_0^1 g_{s,ij}(\gamma_s) \dot{\gamma}_s^i \dot{\gamma}_s^j dt ds \\ &= \int_0^1 \int_0^1 f_{\alpha\beta}(\gamma_s) \dot{\gamma}_s^\alpha \dot{\gamma}_s^\beta dt ds, \end{aligned}$$

where $f = g_1 - g_0$, and the Greek symbols vary from 1 to $n - 1$. The terms coming from differentiating γ_s above vanish because of the minimizing property of γ_s for each fixed s . Notice that (x', x^n) are boundary normal coordinates related to g_s for each $s \in [0, 1]$, too, as a consequence of the fact that $(g_s)_{ij} = \delta_{ij}$. Indeed, one can easily verify that for $\varepsilon_0 \ll 1$, the curve $[0, \varepsilon_0] \ni t \mapsto (0, \dots, 0, 1)$ is a geodesic w.r.t. g_s with t the arc-length and it is perpendicular to the boundary $x^n = 0$. Introduce

$$(7.2) \quad I_s f(\varepsilon; x', p') = \int_0^1 f_{\alpha\beta}(\gamma_s) \dot{\gamma}_s^\alpha \dot{\gamma}_s^\beta dt.$$

This is the geodesic X-ray transform that we studied before, related to g_s , and written in different coordinates. Then (7.1) can be written as

$$(7.3) \quad \rho_{g_1}^2(\varepsilon; x', p') - \rho_{g_0}^2(\varepsilon; x', p') = \int_0^1 I_s f(\varepsilon; x', p') ds.$$

Our next goal is to see that the Taylor expansion of $I_s f$ at $\varepsilon = 0$ determines all derivatives of f , and to use (7.3) to derive the same conclusion about the non-linear problem.

In what follows, we work with $g = g_s$ and we will drop the subscript s . By the geodesic equation,

$$(7.4) \quad \ddot{\gamma}^n + \Gamma_{\alpha\beta}^n(\gamma) \dot{\gamma}^\alpha \dot{\gamma}^\beta = 0.$$

In our coordinates, $\Gamma_{\alpha\beta}^n = -\frac{1}{2} \partial g_{\alpha\beta} / \partial x^n$, and the second fundamental form on $\partial\Omega$ is given by $\Gamma_{\alpha\beta}^n p^\alpha p^\beta$. By the strong convexity assumption, the latter is a positive quadratic form. In particular, we get that the same is true for each $s \in [0, 1]$, with a uniform constant. Set $t = 0$ in (7.4) to get

$$\ddot{\gamma}^n(0) = -\Gamma_{\alpha\beta}^n(x', 0) \theta^\alpha \theta^\beta,$$

where $\theta = \dot{\gamma}(0)$. Therefore (see also [Sh1]),

$$\gamma^n(t) = t\theta^n - \frac{t^2}{2} \Gamma_{\alpha\beta}^n(x', 0) \theta^\alpha \theta^\beta + O(t^3),$$

for θ with a fixed length. In our case we have $\theta = \dot{\gamma}(0) = \exp_{(x',0)}^{-1}(x' + \varepsilon p', 0) = \varepsilon p' + O(\varepsilon^2)$, so in particular, $|\theta| = O(\varepsilon)$. Replace θ by $\theta/|\theta|$, and t by $t|\theta|$ above. Then,

$$(7.5) \quad \gamma^n(t) = t\theta^n - \frac{t^2}{2} \Gamma_{\alpha\beta}^n(x', 0) \theta^\alpha \theta^\beta + O(\varepsilon^3).$$

Since $\gamma^n(1) = 0$, we get $\theta^n = \frac{1}{2} \Gamma_{\alpha\beta}^n \theta^\alpha \theta^\beta + O(\varepsilon^3)$. Plug this into (7.5) to get

$$(7.6) \quad \gamma^n(t) = \frac{\varepsilon^2}{2} \Gamma_{\alpha\beta}^n(x', 0) p^\alpha p^\beta (t - t^2) + O(\varepsilon^3).$$

Now let $f = f^{(0)}(x') + x^n f^{(1)}(x') + \dots$ be the Taylor expansion of f near $x^n = 0$. Plug this into (7.2) to get

$$(7.7) \quad I f = \varepsilon^2 f_{\alpha\beta}^{(0)}(x') p^\alpha p^\beta + O(\varepsilon^3).$$

This recovers $f_{\alpha\beta}^{(0)}(x') p^\alpha p^\beta$. It is easy to see that any symmetric tensor h can be recovered by $h_{ij} p^i p^j$, which is known for some finite number $\{p_l\}$ of p 's, and moreover, this can be done in a stable way, i.e., we also have $|h| \leq C \sup_l |h_{ij} p_i^i p_l^j| / |p_l|^2$ with C depending on the set. Thus we get

$$\frac{1}{2} \frac{d^2}{d\varepsilon^2} \Big|_{\varepsilon=0} I_s f = f_{\alpha\beta}^{(0)}(x') p^\alpha p^\beta,$$

and in particular, the l.h.s. above is independent of s . This implies the estimate

$$(7.8) \quad \|f(x', 0)\|_m \leq C \|\rho_{g_1}^2 - \rho_{g_0}^2\|_{2+m}.$$

To study the higher-order terms in (7.7), we will plug the Taylor series of f w.r.t. x^n into (7.2); therefore we need first to study integrals of $(x^n)^k f^{(k)}(x')$ over γ . Observe first that one can expand $\gamma(t)$ into a finite Taylor series in powers of ε , similar to the second-order expansion for γ^n in (7.6). Next, $f^{(k)}(\gamma'(t)) = f^{(k)}(x', 0) + O(\varepsilon)$, and the remainder can be expanded using higher-order derivatives of $f^{(k)}$. So we get

$$(7.9) \quad \begin{aligned} & \int_0^1 (\gamma^n)^k f_{\alpha\beta}^{(k)}(\gamma') \dot{\gamma}^\alpha \dot{\gamma}^\beta dt \\ &= \varepsilon^{2k+2} (1 + O(\varepsilon)) \left(\frac{1}{2} \Gamma_{\alpha\beta}^n(x', 0) p^\alpha p^\beta \right)^k f_{\alpha\beta}^{(k)}(x', 0) p^\alpha p^\beta \int_0^1 (t - t^2)^k dt \\ &= C_k \varepsilon^{2k+2} (\Gamma_{\alpha\beta}^n(x', 0) p^\alpha p^\beta)^k f_{\alpha\beta}^{(k)}(x', 0) p^\alpha p^\beta + \varepsilon^{2k+3} \Psi_k, \end{aligned}$$

where $C_k > 0$, $\Psi_k = \Psi_{k0} + \Psi_{k1}\varepsilon + \Psi_{k2}\varepsilon^2 + \dots$, and

$$(7.10) \quad \|\Psi_{kj}\|_m \leq C \|f^{(k)}\|_{m+j+1},$$

with C above uniform for any fixed collection of indices if g_0 and g_1 are bounded in C^{m+j+2} .

Consider the fourth-order term in (7.7). By (7.9) and (7.2), it involves $f^{(0)}$ and $f^{(1)}$ only and we therefore get

$$\frac{1}{4!} \frac{d^4}{d\varepsilon^4} \Big|_{\varepsilon=0} I_s f = C_1 \Gamma_{\alpha\beta}^n(x', 0) p^\alpha p^\beta f_{\alpha\beta}^{(1)}(x', 0) p^\alpha p^\beta + \Psi_{01}, \quad C_1 > 0.$$

We integrate the above in s from 0 to 1, use the fact that $\int_0^1 \Gamma_{\alpha\beta}^n p^\alpha p^\beta ds > c_0 |p|^2$ with some $c_0 > 0$ independent of s by the strong convexity assumption, and use (7.10), (7.8) to estimate Ψ_{01} to get

$$\|f^{(1)}\|_m \leq C \|\rho_{g_1}^2 - \rho_{g_0}^2\|_{4+m},$$

and C is uniform if g_0 and g_1 are bounded in C^{m+2} .

For general $k \geq 1$, the formula above generalizes to

$$(7.11) \quad \frac{1}{(2k+2)!} \frac{d^{2k+2}}{d\varepsilon^{2k+2}} \Big|_{\varepsilon=0} I_s f = C_k (\Gamma_{\alpha\beta}^n(x', 0) p^\alpha p^\beta)^k f_{\alpha\beta}^{(k)}(x', 0) p^\alpha p^\beta + \sum_{2k'+j=2k-1} \Psi_{k'j},$$

$C_k > 0$. Now, we can prove the following estimate by induction:

$$(7.12) \quad \|f^{(k)}\|_m \leq C \|\rho_{g_1}^2 - \rho_{g_0}^2\|_{2+2k+m},$$

and this estimate requires $m + 2k + 3$ uniformly bounded derivatives of g_0 and g_1 .

To complete the proof of the theorem, it is enough to notice that for a fixed p' , $d/d\varepsilon$ is a certain directional derivative w.r.t. y , and we need a finite set of p' 's. The coordinate change required to pass to the original coordinates increases the needed number of derivatives of g by 2, which explains the factor $m + 2k + 5$ in the theorem. \square

7.2. Interior stability; proof of Theorem 1.8. Fix $g_0 \in \mathcal{G}^k$, $k \geq k_0$, and let g and \tilde{g} be two metrics as g_1 and g_2 in Theorem 1.8 with some $A > 0$ and $\varepsilon_0 \ll 1$, i.e.,

$$(7.13) \quad \|g\|_{C^k(\bar{\Omega})} + \|\tilde{g}\|_{C^k(\bar{\Omega})} \leq A, \quad \|g - g_0\|_{C(\bar{\Omega})} + \|\tilde{g} - g_0\|_{C(\bar{\Omega})} \leq \varepsilon_0.$$

The first condition above is a typical compactness condition. Using the interpolation estimate [Tri]

$$(7.14) \quad \|f\|_{C^t(\bar{\Omega})} \leq C \|f\|_{C^{t_1}(\bar{\Omega})}^{1-\theta} \|f\|_{C^{t_2}(\bar{\Omega})}^\theta, \quad t = (1 - \theta)t_1 + \theta t_2,$$

where $0 < \theta < 1$, $t_1 \geq 0$, $t_2 \geq 0$, one gets that $\|g - g_0\|_{C^t(\bar{\Omega})} \leq C(A)\varepsilon_0^{(k-t)/k}$ for each $s \geq 0$, if $k > t$; the same is true for \tilde{g} . For our purposes, it is enough to apply (7.14) with t , t_1 and t_2 integers only. Then (7.14) easily extends to compact manifolds with or without boundary. Set

$$(7.15) \quad \delta = \|\rho^2 - \tilde{\rho}^2\|_{C(\partial\Omega \times \partial\Omega)}.$$

Here and below, a tilde above an object indicates that it is associated with \tilde{g} . Using interpolation estimates again, for any $\mu < 1$, we get

$$(7.16) \quad \|\rho^2 - \tilde{\rho}^2\|_{C^m(\partial\Omega \times \partial\Omega)} \leq C\delta^\mu$$

with $C = C(A, \mu, m)$, as long as k is large enough. Here, as in Theorem 7.1, we prefer to work with the squares of ρ , $\tilde{\rho}$ because they are smooth functions with derivatives of any fixed order bounded by $C(A)$, if $k \gg 1$.

In what follows, we denote by $\mu < 1$ constants arbitrarily close to 1 that may change from step to step. We also denote by C various constants depending only on Ω , A , μ , and on the choice of k in (7.13). Our goal is to show that for any such μ , there exists $k \gg 1$, and $\varepsilon_0 > 0$, such that the estimate in Theorem 1.8 holds. We will often use the notation $k \geq k_1(\mu) \gg 1$ to indicate that the corresponding statement holds for k large enough, depending on μ .

By Theorem 7.1, one can choose a diffeomorphic copy of \tilde{g} , which will be denoted by \tilde{g} again, such that the stability estimate in Theorem 7.1 holds, i.e.,

$$(7.17) \quad \|\partial_\nu^l(g - \tilde{g})\|_{C^m(\partial\Omega)} \leq C\delta^\mu, \quad \forall l, m, \forall \mu < 1$$

as long as $k \geq k_1(\mu, m + 2l) \gg 1$, where ∂_ν is the normal derivative. Estimates (7.13) will be replaced by similar ones as in Section 6. Without loss of generality we may assume that the original estimates (7.13) are still satisfied.

Below, we will modify the starting metrics g and \tilde{g} several times, and each subsequent pair will be denoted by g_l , \tilde{g}_l , where $l = 1, 2, 3, 4$. The corresponding ρ 's will be denoted by ρ_l , $\tilde{\rho}_l$.

Construction of g_1 and \tilde{g}_1 . First, we modify \tilde{g} near $\partial\Omega$ by replacing it there by g in a small δ -dependent neighborhood. Let $\chi \in C^\infty(\mathbf{R})$, such that $\chi(t) = 1$ for $t < 1$, and $\chi(t) = 0$ for $t \geq 2$. Let $M > 0$ be a large parameter that will be specified later. Set

$$(7.18) \quad \tilde{g}_1 = \tilde{g} + \chi(\delta^{-1/M} \rho(x, \partial\Omega))(g - \tilde{g}), \quad g_1 = g.$$

Using Taylor's expansion of g and \tilde{g} up to $O((x^n)^M)$, where $x^n = \rho(x, \partial\Omega)$, and estimate (7.17), we see that for any $m \geq 0$,

$$(7.19) \quad \|\tilde{g}_1 - \tilde{g}\|_{C^m(\bar{\Omega})} \leq C\delta^{\mu-m/M}, \quad \forall \mu < 1,$$

provided that $k \geq k(M, m, \mu)$. We extend g_1 and \tilde{g}_1 in a small neighborhood Ω_1 of Ω , such that the extended metrics are still simple there and equal. If $\delta \ll 1$, then (7.13) holds with A and ε there multiplied by a constant. The modified metrics then satisfy

$$(7.20) \quad g_1 = \tilde{g}_1 \quad \text{for } -1/C \leq x^n \leq \delta^{1/M},$$

where x^n is the normal coordinate in a collar neighborhood of $\partial\Omega$. In view of (7.19), it is enough to estimate $g_1 - \tilde{g}_1$.

We will use the following observation in what follows. If g_1, \tilde{g}_1 are ϵ -close in C^k with some k , then the corresponding Hamiltonian flows $\Phi^t(x, \xi)$ and $\tilde{\Phi}^t(x, \xi)$ are $O(\epsilon)$ -close on any compact set in the C^{k-2} topology w.r.t. the variables t, x, ξ . This follows from the fact that the Hamiltonian vector fields are $O(\epsilon)$ -close in C^{k-1} , and if they have $k - 1$ continuous derivatives w.r.t. a parameter, the same is true for the solution (see e.g. [A]) with upper bounds depending on those of the derivatives of order ≥ 1 of the Hamiltonian field. Now, one can define g_s as above, choose s to be that parameter, and apply the mean value theorem for $0 \leq s \leq 1$.

The argument above shows, in particular, that the distance functions $\tilde{\rho}_1$ and $\tilde{\rho}$ related to \tilde{g}_1 and \tilde{g} , respectively satisfy

$$(7.21) \quad \|\tilde{\rho}_1^2 - \tilde{\rho}^2\|_{C^{m-2}(\partial\Omega \times \partial\Omega)} \leq C\delta^{\mu-m/M}, \quad \forall \mu < 1,$$

for any m , if $k \geq k(m, M, \mu)$. To prove this, we write $\rho^2(x, y) = |\exp_x^{-1} y|^2$. Therefore, by choosing $M \gg 1$, we can arrange the estimate (7.16) for $\rho_1^2 - \tilde{\rho}_1^2$ for each fixed m by writing $\rho_1^2 - \tilde{\rho}_1^2 = (\rho^2 - \tilde{\rho}^2) + (\tilde{\rho}^2 - \tilde{\rho}_1^2)$, i.e.,

$$(7.22) \quad \|\rho_1^2 - \tilde{\rho}_1^2\|_{C^m(\partial\Omega \times \partial\Omega)} \leq C\delta^\mu, \quad \forall \mu < 1,$$

as long as M and k are large enough, depending on m and μ .

Construction of g_2 and \tilde{g}_2 . Following the proof of Lemma 4.2, choose $x_0 \in \Omega_1 \setminus \bar{\Omega}$, and let $\psi : \Omega \rightarrow W := \psi(\Omega)$ be the corresponding diffeomorphism related to g_1 . Set also $W_1 = \psi(\Omega_1)$. Denote

$$(7.23) \quad g_2 = \psi_* g_1, \quad \tilde{g}_2 = \psi_* \tilde{g}_1 \quad \text{in } W.$$

Then the straight lines $x' = \text{const.}$ are geodesics for g_2 but not necessarily for \tilde{g}_2 . We also have $(g_2)_{in} = \delta_{in}, \forall i$.

Let $\partial W_\mp \subset \partial W$ be the set of those points $x \in \partial W$ with the property that the vector $\pm e_n$ at x points into W (see also (4.5)). For any $x \in W$, let $p(x) \in \partial W_-$, $q(x) \in \partial W_+$ be the endpoints of the line segment in W through x parallel to e_n . We will define a new diffeomorphism ϕ fixing ∂W in the following way. Set

$$(7.24) \quad \phi(x) = \widetilde{\text{exp}}_{p(x)} \frac{\tilde{\rho}_2(p(x), q(x))}{|p(x) - q(x)|} |x - p(x)| \tilde{\xi}(x), \quad \tilde{\xi}(x) = -\nabla_p \tilde{\rho}_2(p(x), q(x)),$$

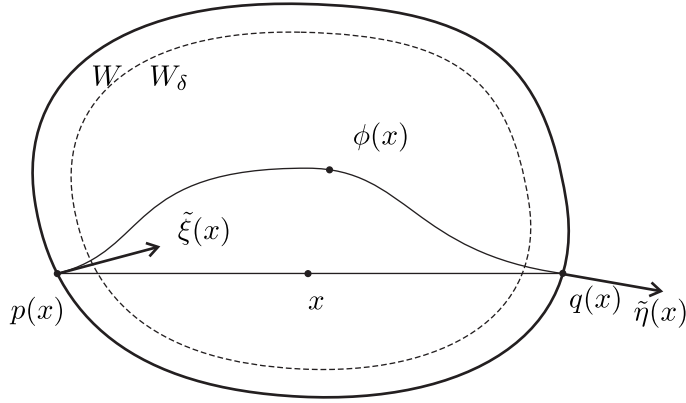


FIGURE 1. The diffeomorphism ϕ

where $|\cdot|$ is the Euclidean norm, and $\widetilde{\text{exp}}$ is related to \tilde{g}_2 . The map ϕ is chosen so that $\phi(W) = W$ and $\phi = \text{Id}$ on ∂W . Next, ϕ also extends into a neighborhood of W . Note that ϕ maps the straight lines parallel to e_n into geodesics for \tilde{g}_2 .

The motivation for choosing ϕ in such a way comes from an observation made by Michel [Mi]. Since by (7.20), $g_2 = \tilde{g}_2$ on ∂W , then $\rho_2 = \tilde{\rho}_2$ on $(\partial W)^2$ would imply $\tilde{\xi}(x) = e_n$. This is implied by the following: by differentiating $\rho_2(x, y) = \tilde{\rho}_2(x, y)$ w.r.t. $x \in \partial W$, for any $y \in \partial W$, we get that the tangential gradients $\nabla' \rho_2$ and $\nabla' \tilde{\rho}_2$ coincide on $(\partial W)^2$. This also allows us to conclude that the full gradients are the same because their lengths are equal (to 1); more precisely, in boundary normal coordinates,

$$(7.25) \quad \frac{\partial \rho_2}{\partial x^n} = \sqrt{1 - g_2^{\alpha\beta} \frac{\partial \rho_2}{\partial x^\alpha} \frac{\partial \rho_2}{\partial x^\beta}} = \frac{\partial \tilde{\rho}_2}{\partial x^n}.$$

In our case, this implies $\tilde{\xi} = e_n$ (under the assumptions $g_2 = \tilde{g}_2$ on ∂W , $\rho_2 = \tilde{\rho}_2$ on $(\partial W)^2$). Then $\phi = \phi_0$, where

$$(7.26) \quad \phi_0 = \widetilde{\text{exp}}_{p(x)} |x - p(x)| e_n = \psi \circ \tilde{\psi}^{-1}.$$

Above, $\tilde{\psi}$ is defined as ψ in Lemma 4.2 but related to \tilde{g}_1 . The second identity above shows that ϕ_0 is a diffeomorphism between W and $\phi_0(W)$ that can be extended near W as well. Below we estimate $\phi - \phi_0$ in terms of δ , if ρ_2 and $\tilde{\rho}_2$ are not equal on the boundary but satisfy (7.22), which is also true for $\rho_2, \tilde{\rho}_2$.

We are going to use (7.20) here in a very essential way. For $\delta \ll 1$, set

$$(7.27) \quad W_\delta = \{x \in W; \rho_2(x, \partial W) > \delta^{1/M}/C\}.$$

We choose $C > 0$ so that $g_2 = \tilde{g}_2$ for $x \notin W_\delta$; see (7.20). Because of (7.20), the possible singularities in (7.24) connected to x , where the ray $s \rightarrow x + se_n$ is tangent to ∂W , are non-existent because $\phi = \text{Id}$ near such rays.

Observe first that $C > 0$ exists such that if $|x - y| \leq \delta^{1/2M}/C$ and $x, y \in \partial W$. Then $\tilde{\rho}_2(x, y) = \rho_2(x, y)$. We claim that this shows that for any m ,

$$(7.28) \quad |\partial_x^m (\tilde{\xi}(x) - e_n)| \leq C\delta^\mu, \quad \left| \partial_x^m \left(\frac{\tilde{\rho}_2(p(x), q(x))}{|p(x) - q(x)|} - 1 \right) \right| \leq C\delta^\mu, \quad \forall \mu < 1,$$

as long as $M \geq M_1(\mu, m) \gg 1$ and $k \geq k_1(\mu, M, m) \gg 1$. For $m = 0$, the second inequality follows directly from the observation above and (7.22), (7.23) by writing $\tilde{\rho}_2 - \rho_2 = (\tilde{\rho}_2^2 - \rho_2^2)/(\tilde{\rho}_2 + \rho_2)$. To prove the first inequality for $m = 0$, we need to estimate $\nabla_p(\tilde{\rho}_2(p(x), q(x)) - \rho_2(p(x), q(x)))$ for $|p(x) - q(x)| \geq \delta^{1/(2M)}/C$. We do this for the tangential gradient by first using (7.22) again and choosing $M \gg 1$. Then we estimate the remaining normal component of the gradient by using (7.25) (note that x^n is a normal coordinate in (7.25) and is not the same as x^n in the fixed coordinate system in W that we are using). This is done by using the estimate for the tangential gradient of $\tilde{\rho}_2 - \rho_2$ and the fact that $|\partial \tilde{\rho}_2 / \partial x^n| \geq \delta^{1/(2M)}/C$, $|\partial \rho_2 / \partial x^n| \geq \delta^{1/(2M)}/C$ (which follows by differentiating (7.6)) for $|p(x) - q(x)| < 1/C$ with $C \gg 1$, and by the simplicity condition for $|p(x) - q(x)| \geq 1/C$. This proves (7.28) for $m = 0$. If $|m| > 0$, then (7.28) follows from the arguments above and the fact that each subsequent derivative of $|p(x) - q(x)|^{-1}$, or $(\tilde{\rho}_2(p(x), q(x)))^{-1}$, contributes a factor of the kind $\delta^{-1/(2M)}$, and a finite product of such a factor can be estimated by $\delta^{-\kappa}$ for each $\kappa > 0$ small enough, if $M \gg 1$, which can be absorbed by the term δ^μ .

Those estimates hold near W as well; thus $|\phi - \phi_0| \leq C\delta^\mu$ in a neighborhood of W . Therefore, we proved that

$$(7.29) \quad \|\phi - \phi_0\|_{C^m(\bar{W}')} \leq C\delta^\mu, \quad \forall \mu < 1$$

for any m , as long as $k \geq k(m, \mu)$ is large enough. In particular, (7.29) shows that ϕ is a diffeomorphism for $\delta \ll 1$.

Construction of g_3 and \tilde{g}_3 . Set

$$(7.30) \quad g_3 = g_2, \quad \tilde{g}_3 = \phi^* \tilde{g}_2.$$

Then, as mentioned above, the straight lines parallel to e_n are geodesics for \tilde{g}_3 , with s proportional to the geodesic arc-length but the coefficient of proportionality depends the line. Next, by Lemma 4.2 and (7.29),

$$(7.31) \quad (g_3)_{in} = \delta_{in}, \quad \|(\tilde{g}_3)_{in} - \delta_{in}\|_{C^m(W)} \leq C\delta^\mu, \quad \forall \mu < 1, \quad \forall i,$$

for any fixed $m > 0$, $\mu < 1$, as long as $M \gg 1$, $k \gg 1$.

The new pair of metrics g_3 and \tilde{g}_3 may not satisfy (7.20) anymore, but we will show that they are close in $W \setminus W_\delta$. More precisely, we claim that

$$(7.32) \quad \sup_{|\alpha| \leq m} |\partial^\alpha(\phi(x) - x)| \leq C\delta^\mu, \quad \text{for } x \in \bar{W} \setminus W_\delta$$

for any $\mu < 1$, m , as long as $M \gg 1$ and $k \gg 1$, depending on μ and m .

To prove (7.32), observe that (7.24) can be written also as

$$(7.33) \quad \phi(x) = \widetilde{\text{exp}}_{q(x)} \frac{\tilde{\rho}_2(p(x), q(x))}{|p(x) - q(x)|} |q(x) - x| (-\tilde{\eta}(x)), \quad \tilde{\eta} = \nabla_q \tilde{\rho}_2(p(x), q(x)).$$

For $\delta \ll 1$, W_δ is also convex w.r.t. g_2 . Therefore, for any $x \in W$, we have that the ray $s \mapsto x + se_n$ intersects ∂W_δ in $m = 0, 1$ or 2 points. If $m = 0$, then along that ray, $g_2 = \tilde{g}_2$ by (7.20); therefore, $\phi(x) = x$. If $m = 1$ or $m = 2$, then either the line segment $[p(x), x]$ is entirely in $W \setminus W_\delta$, or this is true for $[x, q(x)]$. In the first case we use (7.24), in the second case — (7.33). Assume that we have the first case. Then $g_2 = \tilde{g}_2$ near the ray $[x, p(x)]$; therefore $\phi = \phi_0$ near x , and (7.32) follows from (7.29). Assume next that we have the second case above. Then we use (7.33),

and estimates (7.28) for $\tilde{\xi}$ replaced by $\tilde{\eta}$, and argue as in the proof of (7.29). Note that our choice of x allows us to replace $\widetilde{\exp}$ by \exp in (7.33) in this case.

Estimate (7.32), combined with (7.30), (7.27) implies

$$(7.34) \quad \sup_{|\alpha| \leq m} |\partial^\alpha (g_3 - \tilde{g}_3)| \leq C\delta^\mu, \quad \text{for } x \in W \setminus W_\delta$$

for large k and M .

Construction of g_4 and \tilde{g}_4 . We will repeat the argument (7.18). Set

$$(7.35) \quad \tilde{g}_4 = \tilde{g}_3 + \chi(C\delta^{-1/M} \rho_3(x, \partial W))(g_3 - \tilde{g}_3), \quad g_4 = g_3,$$

where $C > 0$ is as in (7.27). Then by (7.34), for any $m \geq 0, \mu < 1$,

$$(7.36) \quad \sup_{|\alpha| \leq m} |\partial^\alpha (\tilde{g}_4 - \tilde{g}_3)| \leq C\delta^\mu, \quad \forall x \in W,$$

as long as $M \geq M_1(m, \mu) \gg 1, k \geq k_1(m, \mu, M) \gg 1$. The advantage that we have with the new metrics g_4, \tilde{g}_4 , is that they coincide near ∂W , i.e.,

$$(7.37) \quad g_4 = \tilde{g}_4 \quad \text{for } 0 \leq \rho_4(x, \partial W) \leq \delta^{1/M}/C.$$

Note that $\rho_4 = \rho_3$ but $\tilde{\rho}_4$ and $\tilde{\rho}_3$ may not be equal; instead they satisfy an estimate similar to (7.21). Therefore,

$$(7.38) \quad \|\tilde{\rho}_4^2 - \rho_4^2\|_{C^m(\bar{\Omega})} \leq C\delta^\mu,$$

for any $m > 0$ and $\mu < 1$ with $M \gg 1, k \gg 1$.

Proof of the stability estimate. We are ready to linearize the problem now and finish the proof of the stability estimate. Set

$$(7.39) \quad f = \tilde{g}_4 - g_4.$$

Then $f = 0$ near ∂W by (7.37), and we extend it as zero outside of W . Arguing as in [SU3], write

$$(7.40) \quad \tilde{\rho}_4 - \rho_4 = \frac{1}{2} I_{g_4} f + R(f)(x, y), \quad (x, y) \in (\partial W)^2,$$

where $y = \exp_x \xi / |\exp_x \xi|$ (the norm here is the same for both metrics because of (7.37)), and the exponential map is in the metric g_4 . The remainder term satisfies [SU3]

$$(7.41) \quad |R(f)(x, y)| \leq C|x - y| \|f\|_{C^1(\bar{W})}^2,$$

with $C = C(A)$, and $k = 2$ suffices for this estimate. By (7.37), (7.38), $\tilde{\rho}_4 - \rho_4 = O(\delta^\mu), \forall \mu < 1$, if $M \gg 1, k \gg 1$ depending on μ .

We want to apply $I_{g_4}^*$ to both sides of (7.40). One can show that for any simple metric g , we have

$$(7.42) \quad [I^*u]_{ij}(y) = \int_{|\omega|=1} u(\gamma_{y,\omega}(\tau_-(y,\omega)), \dot{\gamma}_{y,\omega}(\tau_-(y,\omega))) \omega_i \omega_j \, dS_\omega,$$

where dS_ω is as in Section 2, and $\tau_-(y, \omega) < 0$ is determined by $\gamma_{y,\omega}(\tau_-(y, \omega)) \in \partial W$. Identity (7.42) follows immediately from $(I^*u, h) = (u, Ih)$ and an application of the so-called Santalo formula [Sh1] or arguing as in the proof of Proposition 1 in [SU3].

By (7.42), we have the estimate $\|I_{g_4}^* u\|_{L^\infty(W_1)} \leq C\|u\|_{L^\infty(\Gamma_-)}$. Therefore, (7.40), (7.41) yield

$$(7.43) \quad \|N_{g_4} f\|_{L^\infty(W_1)} \leq C\delta^\mu + C\|f\|_{C^1(\bar{W})}^2,$$

for any $\mu < 1$, as long as $k \geq k(\mu)$.

At this point, we apply the stability estimate for the linear problem. By our assumptions, $g_0 \in \mathcal{G}^k$ for $k \gg 1$, and if ε_0 in (7.13) is small enough, then I_g is s-injective in Ω as well. Then I_{g_4} is s-injective in W . By Theorem 1.5, one has

$$\|f^s\|_{L^2(W)} \leq C\|N_{g_4} f\|_{C^2(W_1)},$$

where we estimated the \tilde{H}^2 -norm by the C^2 -norm. The constant C above depends only on Ω , g_0 , k , and ε_0 . Recall that f is supported strictly in W . Using the interpolation estimate (7.14) again, and continuity properties of the Ψ DO N_{g_3} , if $k \gg 1$, we get by (7.43),

$$(7.44) \quad \|f^s\|_{L^2(W)} \leq C \left(\delta^\mu + \|f\|_{C^1(\bar{W})}^2 \right)^{\mu_1},$$

for any $\mu_1 < 1$, $\mu < 1$, $k \gg 1$, with k, C depending on μ, μ_1 .

By (7.31), (7.36), $f_{in} = O(\delta^\mu)$, $\forall i$. This estimate and (7.37), (7.39) allow us to estimate $\|f^s\|_{H^2}$ from below by $\|f\|$ modulo $O(\delta^\mu)$. One can express v related to f in terms of f and f^s by solving $dv = f - f^s$; see (4.5). Write $f = f^s + dv$. Then $[dv]_{nn} = \partial_{x^n} v_n = f_{nn} - f_{nn}^s$. Therefore,

$$(7.45) \quad v_n(x) = \int_{\tau_-(x)}^0 (f_{nn} - f_{nn}^s)(x', x^n + s) ds,$$

where $\tau_-(x) < 0$ is determined by $(x', x^n + \tau_-(x)) \in \partial W$. This yields $\|v_n\|_{L^2(W)} \leq C(\|f^s\|_{L^2(W)} + \delta^\mu)$. We use an interpolation inequality similar to (7.14) but for Sobolev spaces, see [Tri], to get $\|v_n\|_{H^1(W)} \leq C(\|f^s\|_{L^2(W)} + \delta^\mu)^{\mu_2}$, $\forall \mu_2 < 1$, if $k \gg 1$. Next, $\nabla_n v_i + \nabla_i v_n = 2(f_{in} - f_{in}^s)$. We write this in the form (4.2), estimate the L^2 -norm of v_i , and then as above, its H^1 -norm. This yields

$$\|v\|_{H^1(W)} \leq C(\|f^s\|_{L^2(W)} + \delta^\mu)^{\mu_2}, \quad \forall \mu < 1, \mu_2 < 1.$$

Therefore, for $f = f^s + dv$ we get

$$(7.46) \quad \|f\|_{L^2(W)} \leq C \left(\|f^s\|_{L^2(W)}^\mu + \delta^\mu \right), \quad \forall \mu < 1.$$

We combine this with (7.44). Therefore,

$$\|f\|_{L^2(W)} \leq C \left(\|f\|_{C^1(\bar{W})}^{2\mu} + \delta^\mu \right),$$

$\forall \mu < 1$, if $k \gg 1$. We can use interpolation again to replace the C^1 -norm above by a $C(\bar{W})$ -norm; and next, the L^2 -norm by a $C(\bar{W})$ -norm. Now, if $1/2 < \mu < 1$, and $\|f\|_{C(\bar{W})} \ll 1$, we get that $\|f\|_{C(\bar{W})} \leq C\delta^\mu$.

We have the following estimates:

$$\begin{aligned} f &= \tilde{g}_4 - g_4 = \tilde{g}_3 - g_3 + O(\delta^\mu) && \text{by (7.33), (7.35)} \\ &= \phi^* \tilde{g}_2 - g_2 + O(\delta^\mu) && \text{by (7.30)} \\ &= \phi^* \psi_* \tilde{g}_1 - \psi_* g_1 + O(\delta^\mu) && \text{by (7.23)} \\ &= \phi^* \psi_* \tilde{g} - \psi_* g + O(\delta^\mu). && \text{by (7.18), (7.19).} \end{aligned}$$

By (7.29), (7.26), $\phi^* \psi_* \tilde{g} = \phi_0^* \psi_* \tilde{g} + O(\delta^\mu) = \tilde{\psi}_* \tilde{g} + O(\delta^\mu)$. Hence,

$$(7.47) \quad f = \tilde{\psi}_* \tilde{g} - \psi_* g + O(\delta^\mu).$$

By (7.13), $\tilde{\psi} = \psi + O(\varepsilon_0)$. This and (7.47) show first that $\|f\|_{C(\bar{W})} \ll 1$, if $\varepsilon_0 \ll 1$; see (7.13). Therefore, by the arguments above, $\|f\|_{C(\bar{W})} \leq C\delta^\mu$. Then (7.47) again implies $\|\tilde{\psi}_* \tilde{g} - \psi_* g\|_{C(\bar{W})} \leq C\delta^\mu$. The estimate in the C^2 -norm is obtained by interpolation.

This completes the proof of Theorem 1.8.

REFERENCES

- [AR] YU. ANIKONOV AND V. ROMANOV, On uniqueness of determination of a form of first degree by its integrals along geodesics, *J. Inverse Ill-Posed Problems*, **5**(1997), no. 6, 487–480. MR1623603 (99f:53072)
- [A] V. ARNOLD, Ordinary Differential Equations, Springer, 1992. MR1162307 (93b:34001)
- [BG] I. N. BERNSTEIN AND M. L. GERVER, Conditions on distinguishability of metrics by hodographs. *Methods and Algorithms of Interpretation of Seismological Information*, Computerized Seismology **13**, Nauka, Moscow, 50–73 (in Russian).
- [BCG] G. BESSON, G. COURTOIS, AND S. GALLOT, Entropies et rigidités des espaces localement symétriques de courbure strictement négative, *Geom. Funct. Anal.*, **5**(1995), 731–799. MR1354289 (96i:58136)
- [B] G. BEYLKIN, Stability and uniqueness of the solution of the inverse kinematic problem in the multidimensional case, *J. Soviet Math.* **21**(1983), 251–254.
- [BQ] F. BOMAN AND E. QUINTO, Support theorems for real-analytic Radon transforms, *Duke Math. J.* **55**(4), 943–948. MR0916130 (89m:44004)
- [Cr] K. C. CREAGER, Anisotropy of the inner core from differential travel times of the phases PKP and PKIPK, *Nature*, **356**(1992), 309–314.
- [C2] C. CROKE, Rigidity for surfaces of non-positive curvature, *Comment. Math. Helv.*, **65**(1990), 150–169. MR1036134 (91d:53056)
- [C1] C. CROKE, Rigidity and the distance between boundary points, *J. Differential Geom.*, **33**(1991), no. 2, 445–464. MR1094465 (92a:53053)
- [CDS] C. CROKE, N. DAIRBEKOV, V. SHARAFUTDINOV, Local boundary rigidity of a compact Riemannian manifold with curvature bounded above, *Trans. Amer. Math. Soc.* **352**(2000), no. 9, 3937–3956. MR1694283 (2000m:53054)
- [Gr] M. GROMOV, Filling Riemannian manifolds, *J. Diff. Geometry* **18**(1983), no. 1, 1–148. MR0697984 (85h:53029)
- [H] G. HERGLOTZ, *Über die Elastizität der Erde bei Berücksichtigung ihrer variablen Dichte*, Zeitschr. für Math. Phys. **52** (1905), 275–299.
- [LSU] M. LASSAS, V. SHARAFUTDINOV AND G. UHLMANN, Semiglobal boundary rigidity for Riemannian metrics, *Math. Ann.*, **325**(2003), 767–793. MR1974568 (2004c:53053)
- [Mi] R. MICHEL, Sur la rigidité imposée par la longueur des géodésiques, *Invent. Math.* **65**(1981), 71–83. MR0636880 (83d:58021)
- [MN] C. MORREY AND L. NIRENBERG, On the analyticity of the solutions of linear elliptic systems of partial differential equations, *Comm. Pure Appl. Math.* **10**(1957), 271–290. MR0089334 (19:654b)
- [Mu1] R. G. MUKHOMETOV, The reconstruction problem of a two-dimensional Riemannian metric, and integral geometry (Russian), *Dokl. Akad. Nauk SSSR* **232**(1977), no. 1, 32–35. MR0431074 (55:4076)
- [Mu2] R. G. MUKHOMETOV, On a problem of reconstructing Riemannian metrics, *Siberian Math. J.* **22**(1982), no. 3, 420–433. MR0621466 (82m:53071)
- [MuR] R. G. MUKHOMETOV AND V. G. ROMANOV, On the problem of finding an isotropic Riemannian metric in an n -dimensional space (Russian), *Dokl. Akad. Nauk SSSR* **243**(1978), no. 1, 41–44. MR0511273 (81a:53059)
- [N] A. NACHMAN, Reconstruction from boundary measurements, *Ann. Math.* **128**(1988), 531–576. MR0970610 (90i:35283)
- [O] J. P. OTAL, Sur les longueurs des géodésiques d’une métrique à courbure négative dans le disque, *Comment. Math. Helv.* **65**(1990), 334–347. MR1057248 (91i:53054)
- [PS] L. PESTOV, V. SHARAFUTDINOV, Integral geometry of tensor fields on a manifold of negative curvature (Russian) *Sibirsk. Mat. Zh.* **29**(1988), no. 3, 114–130; translation in *Siberian Math. J.* **29**(1988), no. 3, 427–441. MR0953028 (89k:53066)

- [PU] L. PESTOV AND G. UHLMANN, Two dimensional simple compact manifolds with boundary are boundary rigid, to appear in *Ann. Math.*
- [Sh1] V. SHARAFUTDINOV, Integral geometry of tensor fields, VSP, Utrech, the Netherlands, 1994. MR1374572 (97h:53077)
- [Sh2] V. SHARAFUTDINOV, An integral geometry problem in a nonconvex domain, *Siberian Math. J.* **43**(6)(2002), 1159–1168. MR1946241 (2003i:53112)
- [ShU] V. SHARAFUTDINOV AND G. UHLMANN, On deformation boundary rigidity and spectral rigidity for Riemannian surfaces with no focal points, *Journal of Differential Geometry*, **56** (2001), 93–110. MR1863022 (2002i:53056)
- [SU1] P. STEFANOV AND G. UHLMANN, Stability estimates for the hyperbolic Dirichlet to Neumann map in anisotropic media, *J. Funct. Anal.* **154**(2) (1998), 330–358. MR1612709 (99f:35120)
- [SU2] P. STEFANOV AND G. UHLMANN, Rigidity for metrics with the same lengths of geodesics, *Math. Res. Lett.* **8**(1–2)(2001), 105–124. MR1618347 (99e:53059)
- [SU3] P. STEFANOV AND G. UHLMANN, Stability estimates for the X-ray transform of tensor fields and boundary rigidity, *Duke Math. J.* **123**(2004), 445–467. MR2068966
- [Ta] M. TAYLOR, Partial Differential Equations, I. Basic Theory. Applied Mathematical Sciences, 115. Springer–Verlag, New York, 1996. MR1395148 (98b:35002b)
- [Tri] H. TRIEBEL, Interpolation Theory, Function Spaces, Differential Operators. North-Holland, 1978. MR0500580 (80i:46032a)
- [Tre] F. TREVES, Introduction to Pseudodifferential and Fourier Integral Operators, Vol. 1. Pseudodifferential Operators. The University Series in Mathematics, Plenum Press, New York–London, 1980. MR0597144 (82i:35173)
- [UW] G. UHLMANN AND J. WANG, Boundary determination of a Riemannian metric by the localized boundary distance function, *Adv. in Appl. Math.* **31**(2003), no. 2, 379–387. MR2001620 (2004j:53043)
- [W] J. WANG, Stability for the reconstruction of a Riemannian metric by boundary measurements, *Inverse Probl.* **15**(1999), 1177–1192. MR1715358 (2000m:53028)
- [WZ] E. WIECHERT AND K. ZOEPFRITZ, Uber Erdbebenwellen, *Nachr. Koenigl. Gesellschaft Wiss., Goettingen* **4**(1907), 415–549.

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