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# Inside-Outside Duality for a Class of Modified Transmission Eigenvalues

Housseem Haddar\*, Moez Khenissi †, Marwa Mansouri ‡§

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## Abstract

We introduce a new modified spectrum associated with the scattering from penetrable objects using the modified background technique. We prove that the inside-outside duality method allows to reconstruct this spectrum from full aperture far field measurements at a fixed frequency. The method is numerically tested and validated on some synthetic examples.

**Key words.** Factorization method, transmission eigenvalues, qualitative methods, inside-outside duality, modified background.

## 1 Introduction

Our objective in this work is to analyze the inside-outside duality method for reconstructing some carefully designed spectra from full aperture far field measurements at a fixed frequency. The inside-outside duality method has been introduced in [10] for identifying Dirichlet eigenvalues from far field measurements. It has been extended to inhomogeneous media in [16] to reconstruct so called transmission eigenvalues [5] but under the assumption that the refractive index is a sufficiently large constant (or small perturbation of a large constant). In order to remove this restriction, the authors in [3] proposed to modify the background in a region containing the inhomogeneity so that it has a refractive index that scales proportionally to  $1/k^2$  where  $k$  is the wave number. We propose in this work to follow this approach but keep the wave number fixed and define as spectral parameter a constant  $\rho$  such that the index of refraction in  $\rho/k^2$  inside the inhomogeneous part of the modified background. We refer to these spectral values as modified transmission eigenvalues. Indeed,

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1 in practice, this option is more interesting as it requires only measurements of the far field  
 2 operator at a fixed wave number. Other modifications of the background have been proposed  
 3 in the literature [2, 4, 7, 6, 8, 9]. However, these modifications would lead to the same diffi-  
 4 culty as for homogeneous backgrounds for the inside-outside duality method. In those cases,  
 5 the use of approaches based on the generalized sampling method would be a possibility [2].  
 6 The latter is numerically more expensive.

7 Following a similar theoretical approach as in [3] we first provide a necessary and sufficient  
 8 on the eigenvalues of a modified far field operator so that  $\rho$  is a modified transmission  
 9 eigenvalue. This result is a consequence of the asymptotic expansion of the solution of the  
 10 scattering problem at a modified transmission eigenvalue when the incident field coincides  
 11 with an eigenfunction. We also prove that an approximation of this eigenfunction can be  
 12 computed.

13 We provide some numerical validating results in a two dimensional setting of the problem.  
 14 We first test the approach for circular domains where the modified transmission eigenvalues  
 15 can be computed as the root of some analytic determinant. For non circular domains we  
 16 compute reference values of the modified transmission eigenvalues by solving the spectral  
 17 problem using a finite element solver. We then validate the inside-outside duality method  
 18 against these numerical values. We show that the method is quite effective and has relative  
 19 robustness with respect to small noise in the data if the domain is convex. The accuracy  
 20 may be deteriorated in the case of non convex domains. Exploiting these values for solving  
 21 some inverse problems is a prospect of the current work. We refer to [1] for a possible use of  
 22 modified transmission eigenvalues in some non destructive testing applications.

23 The paper is organized as follows. In Section 2 we introduce the notion of modified  
 24 transmission eigenvalues and review some known results on the modified far field operator  
 25 and associated factorization. Section 3 contains the statements and the proofs of the main  
 26 theoretical results of this paper, namely necessary and sufficient conditions for  $\rho$  to be an  
 27 eigenvalue in terms of the modified far field operator. Section 4 is dedicated to the numerical  
 28 validation of the method.

## 29 **2 Definition of Modified Transmission Eigenvalues and** 30 **Some Classical Related Results**

### 31 **2.1 Definition of Modified Transmission Eigenvalues**

32 Let  $\Omega \subset \mathbb{R}^3$  be a bounded Lipschitz domain with connected complement and let the refractive  
 33 index  $n \in L^\infty(\mathbb{R})$  be a real valued function such that  $n = 1$  outside  $\Omega$ . Consider an incident  
 34 wave  $u_i$  that satisfies the Helmholtz equation  $\Delta u_i + k^2 u_i = 0$  in  $\mathbb{R}^3$  at the frequency  $k > 0$ .  
 35 The scattering problem can be formulated as: the total field  $u = u_i + u^s$  and is such that

$$\left| \begin{array}{l} \Delta u + k^2 n u = 0 \text{ in } \mathbb{R}^3, \\ \lim_{r \rightarrow +\infty} \int_{|x|=r} \left| \frac{\partial u^s}{\partial r} - i k u^s \right|^2 ds(x) = 0. \end{array} \right. \quad (2.1)$$

1 The last condition is referred to later as the Sommerfeld radiation condition. This problem  
 2 has a unique solution  $u \in H_{\text{loc}}^2(\mathbb{R}^3)$  and the scattered field  $u_s$  has the expansion

$$u^s(r\hat{x}) = \frac{e^{ikr}}{r} \left( u_\infty(\hat{x}) + O(1/r) \right), \quad (2.2)$$

3 as  $r = |x| \rightarrow +\infty$ , uniformly in  $\hat{x} \in \mathbb{S}^2 := \{\theta \in \mathbb{R}^3; |\theta| = 1\}$  (see for instance [5]). The  
 4 function  $u_\infty : \mathbb{S}^2 \rightarrow \mathbb{C}$  is the so-called far field pattern of  $u^s$ . When  $u_i$  coincides with  
 5 the incident plane wave  $u_i(\cdot, d) := e^{ikd \cdot x}$ , with  $d \in \mathbb{S}^2$ , we denote respectively by  $u^s(\cdot, d)$   
 6 and  $u_\infty(\cdot, d)$  the corresponding scattered field and far field pattern. We define the far field  
 7 operator  $F : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$  such that

$$(Fg)(\hat{x}) = \int_{\mathbb{S}^2} g(d) u_\infty(\hat{x}, d) ds(d). \quad (2.3)$$

8 If we define for  $v \in L^2(\Omega)$  a scattered field  $w \in H_{\text{loc}}^2(\mathbb{R}^3)$  that satisfies  $\Delta w + k^2 n w = k^2(1-n)v$   
 9 in  $\mathbb{R}^3$  and the Sommerfeld radiation condition, then by linearity of the scattering problem with  
 10 respect to the incident wave, we obtain  $Fg = w_\infty$ , the far field pattern associated with  $w$   
 11 the solution for  $v = v_g$  in  $\Omega$  where

$$v_g(x) := \int_{\mathbb{S}^2} g(d) e^{ikd \cdot x} ds(d). \quad (2.4)$$

12 It is known, that the set  $\{v_g|_\Omega, g \in L^2(\mathbb{S}^2)\}$  is dense in  $\{\varphi \in L^2(\Omega); \Delta\varphi + k^2\varphi = 0 \text{ in } \Omega\}$ .  
 13 Moreover, the scattering operator  $S : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$  defined by

$$S := \text{Id} + \frac{ik}{2\pi} F \quad (2.5)$$

14 is unitary and the operator  $F$  is normal (see for instance [5, 15, 9]).

15 We define the classical Transmission Eigenvalues (TEs) as the values of  $k > 0$  for which  
 16 there exists a non trivial incident field  $v \in L^2(\Omega)$  for which  $w = 0$  outside  $\Omega$ . This leads to  
 17 the equivalent definition of TEs as the values of  $k \in \mathbb{R}_+^* := (0; +\infty)$  for which the problem

$$\begin{cases} \Delta w + k^2 n w = k^2(1-n)v & \text{in } \Omega \\ \Delta v + k^2 v = 0 & \text{in } \Omega \end{cases} \quad (2.6)$$

18 admits a non trivial solutions  $(v, w) \in L^2(\Omega) \times V_0(\Omega)$ .

19 This definition of TEs uses as a reference media (or background) the vacuum. Similarly  
 20 one can define other transmission eigenvalues by changing this reference media. Let  $n_b \in$   
 21  $L^\infty(\mathbb{R}^3)$  a given real valued function such that  $n_b = 1$  in  $\mathbb{R}^3 \setminus \overline{\Omega_b}$  where  $\Omega_b \supset \Omega$  is a bounded  
 22 Lipschitz domain with connected complement. We denote by  $u_b \in H_{\text{loc}}^2(\mathbb{R}^3)$  the total field  
 23 associated with scattering of the incident plane wave  $u_i$  by the inhomogeneous medium  
 24 defined by the refractive index  $n_b$ . This field satisfies,  $u_b = u_i + u_b^s$  and

$$\Delta u_b + k^2 n_b u_b = 0 \text{ in } \mathbb{R}^3 \quad (2.7)$$

1 and  $u_b^s$  satisfies the Sommerfeld radiation condition. We denote by  $u_b(\cdot, d)$  and  $u_b^s(\cdot, d)$  the  
 2 total and scattered fields associated with  $u_i = u_i(\cdot, d)$ . We define the background far field  
 3 operator  $F^b : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$  by

$$(F^b g)(\hat{x}) := \int_{\mathbb{S}^2} g(d) u_\infty^b(\hat{x}, d) ds(d),$$

4 where  $u_\infty^b(\cdot, d)$  is the far field pattern associated with  $u_b^s(\cdot, d)$ . Similarly to (2.5), we define  
 5 the background scattering operator  $S^b : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$  by

$$S^b := \text{Id} + \frac{ik}{2\pi} F^b. \quad (2.8)$$

6 We then define the modified far field operator  $F^m : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$  as

$$F^m := F - F^b. \quad (2.9)$$

7 Inspired by [3], we make the following specific choice of the values of  $n_b$  inside  $\Omega_b$ , where  
 8  $\rho \in \mathbb{R}$  will play the role of the spectral parameter

$$n_b := \rho/k^2 \text{ in } \Omega_b. \quad (2.10)$$

9 From the definition of  $F$  and  $F^b$ , we observe that  $F^m g = w_\infty$  where  $w_\infty$  is the far field  
 10 pattern associated with  $w \in H_{\text{loc}}^2(\mathbb{R}^3)$  satisfying

$$\begin{cases} \Delta w + k^2 n w = k^2 (n_b - n) v \text{ in } \mathbb{R}^3, \\ \lim_{r \rightarrow +\infty} \int_{|x|=r} \left| \frac{\partial w}{\partial r} - ikw \right|^2 ds(x) = 0, \end{cases} \quad (2.11)$$

11 with  $v = u_b$  solution of problem (2.7) with  $u_i$  replaced by  $v = v_g$ . We notice for later use  
 12 that we have, by the well posedness of the scattering problem associated with  $n$ ,

$$\|w\|_{H^2(\Omega_b)} \leq C \|v\|_{L^2(\Omega_b)} \quad (2.12)$$

13 where  $C > 0$  is a constant independent of  $v \in L^2(\Omega_b)$  and independent of  $\rho$  in a compact set  
 14 of  $\mathbb{R}$ . We also recall that the far field  $w_\infty$  associated with this  $w$  can be expressed as

$$w_\infty(\hat{x}) = \frac{1}{4\pi} \int_{\Omega_b} (k^2 (n_b - n) v + k^2 (1 - n) w)(y) e^{-ik\hat{x}\cdot y} ds(y) \quad \forall \hat{x} \in \mathbb{S}^2 \quad (2.13)$$

15 We are now in position to define the modified transmission eigenvalues (MTEs)

16 **Definition 1.** *Let  $k > 0$  be fixed. We define the MTEs as the values of  $\rho \in \mathbb{R}$  for which*  
 17 *there exists  $u_i \in L^2(\Omega_b) \setminus \{0\}$  satisfying  $\Delta u_i + k^2 u_i = 0$  in  $\Omega_b$  and such that the corresponding*  
 18  *$u^s$  and  $u_b^s$  respectively defined via (2.1) and (2.7) are equal outside  $\Omega_b$ .*

1 Clearly, if  $\rho$  is a MTE then we have  $w = 0$  in  $\mathbb{R}^3 \setminus \overline{\Omega_b}$  where  $w$  is the solution of (2.11) with  
 2  $v = u_b$ . Therefore MTEs can be equivalently defined as the values of  $\rho \in \mathbb{R}$  for which there  
 3 exists a non trivial solution  $(v, w) \in L^2(\Omega_b) \times V_0(\Omega_b)$  to the modified interior transmission  
 4 problem

$$\begin{cases} \Delta w + k^2 n w = (\rho - k^2 n) v & \text{in } \Omega_b, \\ \Delta v + \rho v = 0 & \text{in } \Omega_b. \end{cases} \quad (2.14)$$

5 The goal of this paper is to show how the inside-outside duality method can be used to  
 6 characterize MTEs from the knowledge of the operator  $\mathcal{F}^m(\rho)$ . The latter can be in practice  
 7 constructed from the measurement operator  $F$  and the numerically evaluated operator  $F_b(\rho)$ .

## 8 2.2 Collection of some needed technical results

9 We define the Herglotz operator for the background media as  $H(\rho) : L^2(\mathbb{S}^2) \rightarrow L^2(\Omega_b)$  such  
 10 that

$$H(\rho)g := \int_{\mathbb{S}^2} g(d) u_b(\cdot, d) ds(d)|_{\Omega_b}. \quad (2.15)$$

11 We define the operator  $T(\rho) : L^2(\Omega_b) \rightarrow L^2(\Omega_b)$  such that

$$T(\rho)v := \frac{1}{4\pi}(k^2 n - \rho)(v + w(\rho)), \quad (2.16)$$

12 where  $w(\rho) \in H_{\text{loc}}^2(\mathbb{R}^3)$  is the unique solution of (2.11). Following [17, 3, 12], if we consider  
 13 the modified far field operator  $\mathcal{F}(\rho) : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$  defined as  $\mathcal{F}(\rho) := (S_b(\rho))^* F^m(\rho)$ ,  
 14 one has the factorization

$$\mathcal{F}(\rho) = H^*(\rho)T(\rho)H(\rho), \quad (2.17)$$

15 and  $\mathcal{F}(\rho)$  is normal. Moreover, the modified scattering operator  $\mathcal{S}(\rho) : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$   
 16 defined as

$$\mathcal{S}(\rho) := \text{Id} + \frac{ik}{2\pi} \mathcal{F}(\rho) \quad (2.18)$$

17 is unitary.

18 We now collect some known properties of the operator  $T(\rho)$  that can be found in [3].  
 19 First, the continuity of  $\rho \mapsto w(\rho)$  from  $\mathbb{R} \rightarrow H_{\text{loc}}^2(\mathbb{R}^3)$  implies the continuity of  $\rho \mapsto T(\rho)$  in  
 20 the operator norm. The second property is related to the imaginary part of  $T(\rho)$ ,

$$v \in L^2(\Omega_b), \quad 4\pi \Im m(T(\rho)v, v)_{L^2(\Omega_b)} = k \int_{\mathbb{S}^2} |w_\infty|^2 ds, \quad (2.19)$$

21 where  $w_\infty(\rho)$  is the far field pattern associated with  $w(\rho)$ . Additionally, if  $\rho$  is not a MTE  
 22 then  $T(\rho)$  is coercive on  $H_{\text{inc}}(\rho) = \overline{\mathcal{R}(H(\rho))}^{L^2(\Omega_b)} = \{\varphi \in L^2(\Omega_b); \Delta\varphi + \rho\varphi = 0 \text{ in } \Omega_b\}$   
 23 namely

$$|(T(\rho)v, v)_{L^2(\Omega_b)}| \geq \gamma \|v\|_{L^2(\Omega_b)}^2 \quad \forall v \in H_{\text{inc}}(\rho) \quad (2.20)$$

24 for some positive constant  $\gamma$ . We finally indicate some obvious connections between MTEs  
 25 and the operator  $T(\rho)$ . From (2.19), Rellich's Lemma and the unique continuation principle,  
 26 one has that

$$\rho \text{ is a MTE of (2.14)} \Leftrightarrow \exists v \in H_{\text{inc}}(\rho) \setminus \{0\} \text{ such that } \Im m(T(\rho)v, v)_{L^2(\Omega_b)} = 0. \quad (2.21)$$

1 Now let  $(v, w) \in L^2(\Omega_b) \times V_0(\Omega_b)$  be an eigenpair associated with a MTE  $\rho$ . Then indeed  
 2  $v \in H_{\text{inc}}(\rho)$  and using the second Green's formula,

$$\int_{\Omega_b} (T(\rho)v) v dx = \frac{1}{4\pi} \int_{\Omega_b} (k^2 n - \rho)(v + w)v dx = -\frac{1}{4\pi} \int_{\Omega_b} (\Delta w + \rho w)v dx = 0. \quad (2.22)$$

3  
 4 The operator  $T(\rho)$  verifies also the symmetry property

**Lemma 2.** *Let  $\rho \in \mathbb{R}$  and and let  $v, u \in L^2(\Omega_b)$ . Then*

$$\int_{\Omega_b} (T(\rho)v) u dx = \int_{\Omega_b} (T(\rho)u) v dx$$

5 *Proof.* According to the definition of  $T(\rho)$  in (2.16), we have  $T(\rho)v = \frac{1}{4\pi}(k^2 n - \rho)(v +$   
 6  $w_v)$  (respectively  $T(\rho)u = \frac{1}{4\pi}(k^2 n - \rho)(u + w_u)$ ) where  $w_v \in H_{\text{loc}}^2(\mathbb{R}^3)$  (respectively  $w_u \in$   
 7  $H_{\text{loc}}^2(\mathbb{R}^3)$ ) and verify (2.11) (respectively verify (2.11) with  $v = u$ ). Let  $R > 0$  large enough  
 8 such that  $\Omega_b \subset B_R = B(O, R)$ , using Green's formula twice we obtain

$$\begin{aligned} & \int_{B_R} (k^2 n - \rho)(u + w_u)w_v dx = \int_{B_R} (\Delta w_u + \rho w_u)w_v dx \\ & = \int_{\partial B_R} \left( \frac{\partial w_u}{\partial \nu} w_v - \frac{\partial w_v}{\partial \nu} w_u \right) ds + \int_{B_R} w_u (\Delta w_v + \rho w_v) dx \\ & = \int_{B_R} w_u (\Delta w_v + \rho w_v) dx = \int_{B_R} (k^2 n - \rho)(v + w_v)w_u dx \end{aligned}$$

9  
 10  
 11 due to the Sommerfeld radiation condition and the fact that  $w_v$  satisfies (2.11). The desired  
 12 identity can be straightforwardly deduced using the definition of  $T(\rho)$ .  $\square$

13 The analysis below requires also the introduction of the orthogonal projection  $P(\rho) :$   
 14  $L^2(\Omega_b) \rightarrow H_{\text{inc}}(\rho)$ . We here clarify some of the arguments used in [16]. Let us denote  
 15 by  $V_0(\Omega_b)$  the completion of  $\mathcal{C}_0^\infty(\Omega_b)$  with respect to the norm  $\|u\|_{V_0(\Omega_b)}^2 := \|u\|_{L^2(\Omega_b)}^2 +$   
 16  $\|\Delta u\|_{L^2(\Omega_b)}^2$ . From the Green formula, one deduces that  $V_0(\Omega_b)$  is a subspace of  $H_0^1(\Omega_b)$  and  
 17 the Poincaré inequality shows that  $\|\Delta u\|_{L^2(\Omega_b)}$  defines an equivalent norm in this space. In  
 18 order to shorten the notation, below and except other mention, the scalar product in  $L^2(\Omega_b)$   
 19 will be denoted by  $(\cdot, \cdot)$ .

20 **Lemma 3.**  *$P(\rho)$  is explicitly given by*

$$P(\rho)g = g - (\Delta \hat{w}(\rho) + \rho \hat{w}(\rho)), \quad (2.23)$$

21 where  $\hat{w}(\rho) \in V_0(\Omega_b)$  is the unique solution of the variational problem

$$\int_{\Omega_b} (\Delta \hat{w}(\rho) + \rho \hat{w}(\rho))(\Delta \psi + \rho \psi) dx = \int_{\Omega_b} g(\Delta \psi + \rho \psi) dx \quad \text{for all } \psi \in V_0(\Omega_b). \quad (2.24)$$

1 *Proof.* Since  $P(\rho)$  is the orthogonal projection on  $H_{\text{inc}}(\rho)$ , for  $g \in L^2(\Omega_b)$ , we have

$$(P(\rho)g - g, v) = 0 \quad \forall v \in H_{\text{inc}}(\rho). \quad (2.25)$$

2 Since  $v$  verifies  $\Delta v + \rho v = 0$  in  $L^2(\Omega_b)$ , which is equivalent to  $\int_{\Omega_b} (\Delta \psi + \rho \psi) \bar{v} = 0$  for all  
3  $\psi \in \mathcal{C}_0^\infty(\Omega_b)$ , by density,

$$\int_{\Omega_b} (\Delta \psi + \rho \psi) \bar{v} = 0 \quad \forall \psi \in V_0(\Omega_b). \quad (2.26)$$

4 Now using (2.25) and (2.26), we obtain  $P(\rho)g - g \in V(\rho)$  where  $V(\rho)$  is the closure of  
5  $\{\Delta \psi + \rho \psi, \psi \in V_0(\Omega_b)\}$  in  $L^2(\Omega_b)$ . In order to conclude the proof we show that  $V(\rho) = \{\Delta \psi +$   
6  $\rho \psi, \psi \in V_0(\Omega_b)\}$ . To proceed, let  $v \in L^2(\Omega_b)$  such there exists a sequence  $(\psi_n)_n \in V_0(\Omega_b)$  and  
7  $v_n = \Delta \psi_n + \rho \psi_n \rightarrow v$  strongly in  $L^2(\Omega_b)$ . In order to prove that  $(\psi_n)_n$  converges strongly  
8 in  $V_0(\Omega_b)$ , we prove that the norm  $\|\Delta \psi + \rho \psi\|_{L^2(\Omega_b)}$  defines an equivalent norm in  $V_0(\Omega_b)$ .  
9 Using the fact that  $\|\Delta \psi\|_{L^2(\Omega_b)}$  is an equivalent norm in  $V_0(\Omega_b)$ , it is sufficient to prove that  
10  $\|\psi\|_{L^2(\Omega_b)} \leq C \|\Delta \psi + \rho \psi\|_{L^2(\Omega_b)}$  for all  $\psi \in V_0(\Omega_b)$ .

11 We employ a contradiction argument. Suppose there exists a sequence  $(\psi_n)_n \in V_0(\Omega_b)$  such  
12 that  $\|\psi_n\|_{L^2(\Omega_b)} = 1 \forall n \in \mathbb{N}$  and  $\|\Delta \psi_n + \rho \psi_n\|_{L^2(\Omega_b)} \rightarrow_{n \rightarrow \infty} 0$ . This implies  $\|\Delta \psi_n\|_{L^2(\Omega_b)}$  is  
13 bounded, and therefore the sequence  $(\psi_n)_n$  is bounded in  $V_0(\Omega_b)$ . Up to a subsequence, we  
14 conclude that  $\psi_n$  converges to some  $\psi \in V_0(\Omega_b)$  weakly in  $V_0(\Omega_b)$  and strongly in  $L^2(\Omega_b)$ .  
15 The limit  $\psi \in V_0(\Omega_b)$  verifies  $\Delta \psi + \rho \psi = 0$  and therefore  $\psi = 0$  by a unique continuation  
16 argument (the extension by 0 of  $\psi$  verifies  $\Delta \psi + \rho \psi = 0$  in  $\mathbb{R}^3$ ). It also verifies  $\|\psi\|_{L^2(\Omega_b)} = 1$   
17 which is a contradiction.

18 We now conclude from  $P(\rho)g - g \in V_0(\Omega_b)$  that there exists  $\hat{w} \in V_0(\Omega_b)$  such that  $P(\rho)g - g =$   
19  $-(\Delta \hat{w}(\rho) + \rho \hat{w}(\rho))$ . The variational equation (2.24) comes from (2.25). This equation  
20 uniquely determines  $\hat{w}(\rho)$  by the Lax-Milgram theorem thanks to the norm equivalence  
21 indicated above.  $\square$

22 Observe that  $\hat{w}(\rho)$  in Lemma 3 satisfies in the distributional sense

$$(\Delta + \rho)(\Delta + \rho)\hat{w}(\rho) = (\Delta + \rho)g \quad \text{in } \Omega_b. \quad (2.27)$$

23 One can also show that  $\rho \rightarrow P(\rho)$  is continuous and differentiable in the operator norm as  
24 indicated in the following lemma.

25 **Lemma 4.** *The map  $\rho \rightarrow P(\rho)$  is continuous and differentiable and for all  $\rho \in \mathbb{R}$ . Moreover*  
26 *for all  $\rho_0 \in \mathbb{R}$  there is  $\varepsilon > 0$  such that*

$$P(\rho)g = P(\rho_0)g - (\rho - \rho_0) [\Delta \hat{w}'(\rho_0) + \rho_0 \hat{w}'(\rho_0) + \hat{w}(\rho_0)] + (\rho - \rho_0)^2 \mu(\rho) \quad (2.28)$$

27 *where  $\hat{w}'(\rho_0) \in V_0(\Omega_b)$  satisfies  $(\Delta + \rho_0)(\Delta + \rho_0)\hat{w}'(\rho_0) = g - 2(\Delta \hat{w}(\rho_0) + \rho_0 \hat{w}(\rho_0))$  in  $\Omega_b$  and*  
28  *$\mu(\rho)$  is such that  $\|\mu(\rho)\|_{L^2(\Omega_b)} \leq C \|g\|_{L^2(\Omega_b)}$  with  $C > 0$  independent from  $\rho \in ]\rho_0 - \varepsilon, \rho_0 + \varepsilon[$*

29 .

1 *Proof.* It is sufficient to only prove (2.28). In the following the constant  $C$  refers to a constant  
 2 which value may differ but remains independent from  $\rho \in ]\rho_0 - \varepsilon, \rho_0 + \varepsilon[$  for some  $\varepsilon > 0$  fixed  
 3 later. Set  $\eta(\rho) = \hat{w}(\rho) - \hat{w}(\rho_0)$  where  $\hat{w}(\rho) \in V_0(\Omega_b)$  is defined in Lemma 3. From (2.23),

$$P(\rho)g - P(\rho_0)g = -\Delta\eta(\rho) - \rho_0\eta(\rho) - (\rho - \rho_0)\hat{w}(\rho_0) - (\rho - \rho_0)\eta(\rho). \quad (2.29)$$

4 The function  $\eta(\rho) \in V_0(\Omega_b)$  verifies

$$(\Delta + \rho_0)(\Delta + \rho_0)\eta(\rho) = (\rho - \rho_0)g - 2(\rho - \rho_0)\Delta\hat{w}(\rho) - (\rho^2 - \rho_0^2)\hat{w}(\rho) \quad \text{in } \Omega_b. \quad (2.30)$$

5 Denote by  $Q(\rho) : V_0(\Omega_b) \rightarrow V_0(\Omega_b)$  the Riesz representation of the operator defined by left  
 6 hand side of (2.24). We have that  $Q(\rho) = Q(\rho_0) + (\rho - \rho_0)Q_0(\rho)$  where  $Q_0(\rho) : V_0(\Omega_b) \rightarrow$   
 7  $V_0(\Omega_b)$  is uniformly bounded with respect to  $\rho$  in neighbourhood of  $\rho_0$ . Using the Laurent  
 8 series we deduces that  $(Q(\rho))^{-1}$  is uniformly bounded with respect to  $\rho \in ]\rho_0 - \varepsilon, \rho_0 + \varepsilon[$   
 9 for some sufficiently small  $\varepsilon > 0$ . In this sequel, we always assume that  $\rho \in ]\rho_0 - \varepsilon, \rho_0 + \varepsilon[$ .  
 10 Consequently  $\|\hat{w}(\rho)\|_{V_0(\Omega_b)} \leq C\|g\|_{L^2(\Omega_b)}$  and from (2.30)  $\|\eta(\rho)\|_{V_0(\Omega_b)} \leq C|\rho - \rho_0|\|g\|_{L^2(\Omega_b)}$ .  
 11 The function  $\gamma(\rho) := \eta(\rho) - (\rho - \rho_0)\hat{w}'(\rho_0)$  verifies

$$(\Delta + \rho_0)(\Delta + \rho_0)\gamma(\rho) = -2(\rho - \rho_0)\Delta\eta(\rho) - (\rho - \rho_0)^2\hat{w}(\rho) \quad \text{in } \Omega_b$$

12 which implies  $\|\gamma(\rho)\|_{V_0(\Omega_b)} \leq C|\rho - \rho_0|^2\|g\|_{L^2(\Omega_b)}$ . The result of the lemma follows by ob-  
 13 serving that from (2.29), identity (2.28) holds with

$$\mu(\rho) = -\Delta\gamma(\rho) - \rho_0\gamma(\rho) - (\rho - \rho_0)\gamma(\rho).$$

14

□

### 15 3 Analysis of the inside outside duality

16 We first consider the case when  $\rho$  is not a MTE. Since  $\mathcal{F}(\rho)$  is a compact normal operator,  
 17 there is an orthonormal complete basis  $(g_j)_{j \in \mathbb{N}}$  of  $L^2(\mathbb{S}^2)$  such that  $\mathcal{F}(\rho)g_j = \lambda_j g_j$  where  
 18  $\{\lambda_j, j = 1, \dots, +\infty\}$  are the eigenvalues of  $\mathcal{F}(\rho)$  that accumulate at 0. If  $\rho$  is not a MTE  
 19 then  $\mathcal{F}(\rho)$  is injective and therefore  $\lambda_j \neq 0 \forall j \in \{1, \dots, +\infty\}$ . Since  $\mathcal{S}(\rho)$  is unitary,  
 20 the eigenvalues of  $\mathcal{F}(\rho)$  lie on the circle of radius  $2\pi/k$  and centre  $2i\pi/k$ . We set  $\lambda_j :=$   
 21  $2\pi/ik(e^{i\delta_j} - 1)$  with  $\delta_j \in (0, 2\pi)$  so that  $e^{i\delta_j}$  are the eigenvalues of  $\mathcal{S}(\rho)$ .  
 22 The following proposition indicates the region of the complex plane where the  $\lambda_j$  accumulate  
 23 at zero according to the sign of  $k^2n - \rho$ . We refer to [3] for the proof of this result.

24 **Proposition 5.** *Assume that  $\rho$  is not a MTE.*

- 25 • *If  $k^2n - \rho \geq \alpha > 0$  in  $\Omega_b$ , then the sequence  $(\delta_j)$  accumulates only at 0.*
- 26 • *If  $\rho - k^2n \geq \alpha > 0$  in  $\Omega_b$ , then the sequence  $(\delta_j)$  accumulates only at  $2\pi$ .*

1 When  $\rho$  is not a MTE we set

$$\delta_*(\rho) := \min_{j \geq 1} \delta_j \quad \text{if } \rho - k^2 n \geq \alpha > 0 \quad \text{and} \quad \delta_*(\rho) := \max_{j \geq 1} \delta_j \quad \text{if } k^2 n - \rho \geq \alpha > 0 \quad (3.1)$$

2 and denote

$$\lambda_*(\rho) := \frac{2\pi}{ik} (e^{i\delta_*(\rho)} - 1).$$

3 The inside-outside duality method relies on the behaviour of  $\delta_*(\rho)$  as  $\rho$  approaches a MTE.  
 4 The analysis of this behaviour is topic of the following subsections.

### 5 3.1 A sufficient condition for the detection of a MTE

6 In this paragraph, we provide a sufficient condition allowing one to detect a MTE of (2.14).

7 **Theorem 6.** *Let  $\rho_0 \in \mathbb{R}$  and  $I = (\rho_0 - \varepsilon; \rho_0 + \varepsilon) \setminus \{\rho_0\}$  such that no  $\rho \in I$  is a MTE of*  
 8 *(2.14). Assume that there is a sequence  $(\rho_j)$  of elements of  $I$  such that*

$$\lim_{j \rightarrow +\infty} \rho_j = \rho_0 \quad \text{and} \quad \lim_{j \rightarrow +\infty} \delta_*(\rho_j) = \begin{cases} 2\pi & \text{when } k^2 n - \rho_0 \geq \alpha > 0 \\ 0 & \text{when } \rho_0 - k^2 n \geq \alpha > 0. \end{cases}$$

9 Then  $\rho_0$  is a MTE of (2.14). Moreover, the sequence  $(v_j)$ , with

$$v_j := \frac{H(\rho_j)g_j}{\|H(\rho_j)g_j\|_{L^2(\Omega_b)}},$$

10 admits a subsequence which converges strongly to  $v \in L^2(\Omega_b)$ , where  $(v, w)$  is an eigenpair  
 11 of (2.14) associated with  $\rho_0$ . Here  $g_j$  is a normalised eigenfunction of  $\mathcal{F}(\rho)$  associated with  
 12  $\lambda_*(\rho_j)$  and  $w$  satisfies (2.11) with  $\rho = \rho_0$ .

13 *Proof.* The proof follows the lines of a similar result in [3] but we provide the details here  
 14 for the sake of completeness. We consider only the case  $k^2 n - \rho_0 \geq \alpha > 0$  since the other  
 15 one follows replacing  $\mathcal{F}(\rho)$  with  $-\mathcal{F}(\rho)$ . Considering  $j$  sufficiently large we can assume that  
 16  $k^2 n - \rho_j \geq \alpha/2 > 0$ . Set

$$\psi_j := \frac{H(\rho_j)g_j}{\sqrt{|\lambda_*(\rho_j)|}} \in L^2(\Omega_b).$$

17 The sequence  $(\psi_j)$  satisfies, according to the assumptions and the factorisation (2.17),

$$(T(\rho_j)\psi_j, \psi_j) = \frac{\lambda_*(\rho_j)}{|\lambda_*(\rho_j)|} (g_j, g_j)_{L^2(\mathbb{S}^2)} = \frac{\lambda_*(\rho_j)}{|\lambda_*(\rho_j)|} \xrightarrow{j \rightarrow +\infty} -1. \quad (3.2)$$

18 Suppose that  $\rho_0$  is not a MTE. Then the operator  $T(\rho_0)$  is coercive on  $H_{\text{inc}}(\rho_0)$ . We deduce  
 19 from (2.20), the continuity of  $\rho \mapsto T(\rho)$  and the continuity of  $\rho \mapsto P(\rho)$  where  $P(\rho)$  is the  
 20 orthogonal projection defined earlier, that one can choose the coercivity constant  $\gamma$  in (2.20)  
 21 to be independent from  $\rho \in I$ . The identity (3.2) then shows that the sequence  $(\psi_j)$  is

1 bounded in  $L^2(\Omega_b)$  and consequently, up to a subsequence, one can assume that  $(\psi_j)$  weakly  
 2 converges to some  $\psi_0$  in  $L^2(\Omega_b)$ . Since  $\psi_j \in H_{\text{inc}}(\rho_j)$  for all  $j \in \mathbb{N}$ , the weak limit satisfies  
 3  $\Delta\psi_0 + \rho_0\psi_0 = 0$  in  $\Omega_b$ , therefore  $\psi_0 \in H_{\text{inc}}(\rho_0)$ . Let us denote by  $w_j \in H_{\text{loc}}^2(\mathbb{R}^3)$  (resp.  
 4  $w_0 \in H_{\text{loc}}^2(\mathbb{R}^3)$ ) the solution of (2.11) with  $v = \psi_j$ ,  $\rho = \rho_j$  (resp.  $v = \psi_0$ ,  $\rho = \rho_0$ ). From  
 5 (2.19) that

$$4\pi \Im m(T(\rho_j)\psi_j, \psi_j) = k \int_{\mathbb{S}^2} |w^\infty(\rho_j)|^2 ds. \quad (3.3)$$

6 From expression (2.13) we have  $\rho \mapsto w^\infty(\rho)$  from  $\mathbb{R} \rightarrow L^2(\Omega_b)$  is compact and consequently,  
 7 using (3.2)

$$4\pi \Im m(T(\rho_j)\psi_j, \psi_j) \xrightarrow{j \rightarrow +\infty} 4\pi \Im m(T(\rho_0)\psi_0, \psi_0) = 0.$$

8 Therefore  $(\psi_0, w_0)$  is a solution of the interior transmission problem (2.14) for  $\rho = \rho_0$ . The  
 9 hypothesis on  $\rho_0$  implies  $\psi_0 = 0$ . Using the definition of  $T(\rho)$  we have

$$\frac{1}{4\pi}((k^2n - \rho_j)\psi_j, \psi_j) = (T(\rho_j)\psi_j, \psi_j) - \frac{1}{4\pi}((k^2n - \rho_j)\psi_j, w_j) \quad (3.4)$$

10 where  $((k^2n - \rho_j)\psi_j, w_j) \rightarrow ((k^2n - \rho_0)\psi_0, w_0)$  when  $j \rightarrow +\infty$ . The latter property is a con-  
 11 sequence of (2.12) and the fact that  $H^2(\Omega_b)$  is compactly embedded in  $L^2(\Omega_b)$ . Consequently

$$0 \leq ((k^2n - \rho_j)\psi_j, \psi_j) \xrightarrow{j \rightarrow +\infty} -1$$

12 which is a contradiction.

13 We now consider the second part of the theorem. Since  $\|v_j\|_{L^2(\Omega_b)} = 1$ , the sequence  $(v_j)$   
 14 admits a subsequence that we still denote the same, that weakly converges to some  $v \in$   
 15  $L^2(\Omega_b)$ . We have

$$(T(\rho_j)v_j, v_j) = \theta_j \frac{\lambda_\star(\rho_j)}{|\lambda_\star(\rho_j)|} \quad (3.5)$$

16 with  $\theta_j := |\lambda_\star(\rho_j)| / \|H(\rho_j)g_j\|_{L^2(\Omega_b)}^2$ . Using the definition  $\lambda_\star(\rho_j)$  we have  $\theta_j \leq \|T(\rho_j)\|$  and  
 17 therefore by continuity of  $\rho \mapsto T(\rho)$  one conclude that  $\theta_j$  is bounded and can assume up  
 18 to changing the subsequence  $v_j$  that  $\theta_j \rightarrow \theta_0 \geq 0$ . We then conclude from (3.5) that  
 19  $\Im m(T(\rho_j)v_j, v_j) \rightarrow 0$  as  $j \rightarrow +\infty$ . The same arguments as above prove that the pair  $(v, w)$   
 20 solves problem (2.14) for  $\rho = \rho_0$ ,  $w$  being the solution of (2.11) with  $\rho = \rho_0$ . Identity (3.4)  
 21 with  $\psi_j$  is replaced by  $v_j$  and the fact that  $(T(\rho_j)v_j, v_j) \rightarrow -\theta_0 \leq 0$  imply

$$\limsup_{j \rightarrow +\infty} (k^2n - \rho_j)v_j, v_j \leq -((k^2n - \rho_0)v, w) \quad (3.6)$$

22 where we used the strong convergence of  $w_j$  to  $w$  in  $L^2(\Omega_b)$ . Since the pair  $(v, w)$  solves  
 23 (2.14), we have  $((k^2n - \rho_0)(v + w), v) = 0$ . Consequently,

$$\limsup_{j \rightarrow +\infty} ((k^2n - \rho_j)v_j, v_j) \leq ((k^2n - \rho_0)v, v).$$

24 Since  $((\rho_j - \rho_0)v, v) \rightarrow 0$  as  $j \rightarrow +\infty$ , we finally get

$$\limsup_{j \rightarrow +\infty} \alpha \|v_j - v\|_{L^2(\Omega_b)}^2 \leq \limsup_{j \rightarrow +\infty} ((k^2n - \rho_j)(v_j - v), v_j - v) \leq 0,$$

25 which proves that  $(v_j)$  strongly converges to  $v$  in  $L^2(\Omega_b)$  and finishes the proof.  $\square$

### 3.2 Necessary conditions for MTE

In order to derive necessary conditions for the characterization of MTE, we need to study the behaviour of  $(T(\rho)H(\rho)g, H(\rho)g)$  for  $\rho$  approaching some MTE  $\rho_0$ . For that purpose we take the approach in [16]. If  $\rho$  is not a MTE then  $L^2(\mathbb{S}^2) = \overline{\mathcal{R}(\mathcal{F}(\rho))}^{L^2(\mathbb{S}^2)}$  and 1 is not an eigenvalue of  $\mathcal{S}(\rho)$ . Therefore we can define the Cayley transform  $\mathfrak{S}(\rho) : L^2(\mathbb{S}^2) \rightarrow L^2(\mathbb{S}^2)$  as  $\mathfrak{S}(\rho) = i(\text{Id} + \mathcal{S}(\rho))(\text{Id} - \mathcal{S}(\rho))^{-1}$ . This operator is self adjoint, its spectrum is discrete and we have the equivalence:  $e^{i\delta_\star(\rho)}$  is an eigenvalue of  $\mathcal{S}(\rho)$  if and only if  $-\cot(\delta_\star(\rho)/2) \in \mathbb{R}$  is an eigenvalue of  $\mathfrak{S}(\rho)$ . Since  $\mathfrak{S}(\rho)$  is selfadjoint, we can apply Courant-Fischer min-max principle and get in the case  $k^2n - \rho \geq \alpha > 0$  in  $\Omega_b$  (using Proposition 5)

$$-\cot \frac{\delta_\star(\rho)}{2} = \sup_{f \in \mathcal{R}(\mathcal{F})} \frac{(\mathfrak{S}(\rho)f, f)}{\|f\|_{L^2(\mathbb{S}^2)}} = \sup_{g \in L^2(\mathbb{S}^2)} \frac{\Im m(\mathcal{S}(\rho)g, g)}{\Re e(\mathcal{S}(\rho)g, g) - \|g\|_{L^2(\mathbb{S}^2)}^2}.$$

Using expression (2.18) and the factorization (2.17), we obtain

$$-\cot \frac{\delta_\star(\rho)}{2} = \sup_{g \in L^2(\mathbb{S}^2)} \frac{\Re e(\mathcal{F}(\rho)g, g)}{-\Im m(\mathcal{F}(\rho)g, g)}$$

$$= \sup_{g \in L^2(\mathbb{S}^2)} \frac{\Re e(T(\rho)H(\rho)g, H(\rho)g)}{-\Im m(T(\rho)H(\rho)g, H(\rho)g)} = \sup_{\varphi \in H_{\text{inc}}(\rho)} \frac{\Re e(T(\rho)\varphi, \varphi)}{-\Im m(T(\rho)\varphi, \varphi)}.$$

Property 2.21 ensures that the denominator of the previous expression does not vanishes. We summarize these results in the following proposition.

**Proposition 7.** *Assume that  $\rho > 0$  is not a MTE of (2.14).*

1. *Assume that  $k^2n - \rho \geq \alpha > 0$  in  $\Omega_b$ . Then*

$$\cot \frac{\delta_\star(\rho)}{2} = \inf_{\varphi \in H_{\text{inc}}(\rho)} \frac{\Re e(T(\rho)\varphi, \varphi)}{\Im m(T(\rho)\varphi, \varphi)}. \quad (3.7)$$

2. *Assume that  $\rho - k^2n \geq \alpha > 0$  in  $\Omega_b$ . Then*

$$\cot \frac{\delta_\star(\rho)}{2} = \sup_{\varphi \in H_{\text{inc}}(\rho)} \frac{\Re e(T(\rho)\varphi, \varphi)}{\Im m(T(\rho)\varphi, \varphi)}. \quad (3.8)$$

We now state and prove the key technical result of this section.

**Proposition 8.** *Let  $\rho_0$  be a MTE of (2.14) and  $(v_0, w_0) \in L^2(\Omega_b) \times V_0(\Omega_b)$  an associated eigenpair. Then there is  $\varepsilon > 0$  and  $\eta(\rho)$  such that*

$$4\pi(T(\rho)v_0, v_0) = -(\rho - \rho_0) \left( \|v_0\|_{L^2(\Omega_b)}^2 + 2\Re e(v_0, w_0) \right) + (\rho - \rho_0)^2 \eta(\rho) \quad (3.9)$$

for all  $\rho$  such that  $|\rho - \rho_0| \leq \varepsilon$ , where  $|\eta(\rho)| \leq C \|v_0\|_{L^2(\Omega_b)}^2$  with  $C > 0$  independent from  $\rho$ .

1 *Proof.* According to the definition of  $T(\rho)$  in (2.16), we have

$$4\pi(T(\rho)v_0, v_0) = ((k^2n - \rho)(v_0 + w(\rho)), v_0) \quad (3.10)$$

2 where  $w(\rho)$  is the solution of (2.11) with  $v = v_0$ . We remark that, according to the definition  
 3 of MTEs, the solution  $w(\rho_0)$  of (2.11) with  $v = v_0$  and  $\rho = \rho_0$  is such that  $w(\rho_0) = w_0$  in  $\Omega_b$   
 4 and  $w(\rho_0) = 0$  outside  $\Omega_b$ . Let  $w'$  the derivative of  $w$  at  $\rho = \rho_0$  then we have an expansion  
 5 as  $\rho \rightarrow \rho_0$  of the form

$$w(\rho) - w(\rho_0) = (\rho - \rho_0)w' + (\rho - \rho_0)^2\tilde{w}(\rho), \quad (3.11)$$

6 where  $w'$  is independent from  $\rho$  and where  $\tilde{w}(\rho)$  have bounded norm as  $\rho \rightarrow \rho_0$ . Let  $B_R$  a ball  
 7 such that  $\overline{\Omega_b} \subset B_R$  and consider the Dirichlet-to-Neumann operator  $\Lambda(\rho) : H^{1/2}(\partial B_R) \rightarrow$   
 8  $H^{-1/2}(\partial B_R)$  such that  $\Lambda(\rho)\varphi = \partial_\nu\psi$  ( $\nu$  is oriented to the exterior of  $B_R$ ) where  $\psi \in H^1_{\text{loc}}(\mathbb{R}^3 \setminus$   
 9  $B_R)$  is the outgoing function solving

$$\left| \begin{array}{l} \Delta\psi + k^2\psi = 0 \quad \text{in } \mathbb{R}^3 \setminus B_R \\ \psi = \varphi \quad \text{on } \partial B_R. \end{array} \right. \quad (3.12)$$

10 Then we have, for all  $\varphi \in H^1(B_R)$ ,

$$\begin{aligned} (\nabla w(\rho), \nabla \varphi) - k^2(nw(\rho), \varphi) - \langle \Lambda(\rho)w(\rho), \varphi \rangle_{\partial B_R} &= ((k^2n - \rho)v_0, \varphi), \\ (\nabla w(\rho_0), \nabla \varphi) - k^2(nw(\rho_0), \varphi) - \langle \Lambda(\rho_0)w(\rho_0), \varphi \rangle_{\partial B_R} &= ((k^2n - \rho_0)v_0, \varphi) \end{aligned} \quad (3.13)$$

11 where  $\langle \cdot, \cdot \rangle_{\partial B_R}$  denotes the  $H^{-1/2}(\partial B_R) - H^{1/2}(\partial B_R)$  duality product. As  $\rho \rightarrow \rho_0$ , the dif-  
 12 ference of the two lines of (3.13) leads us to prove that  $w' \in H^2_{\text{loc}}(\mathbb{R}^3)$  satisfies, for all  
 13  $\varphi \in H^1(B_R)$ ,

$$(\nabla w', \nabla \varphi) - k^2(nw', \varphi) - \langle \Lambda(k)w', \varphi \rangle_{\partial B_R} = -(v_0, \varphi).$$

14 Using,  $(T(\rho_0)v_0(\rho_0), v_0(\rho_0)) = 0$ , we obtain

$$\begin{aligned} 4\pi(T(\rho)v_0, v_0) &= ((k^2n - \rho)(v_0 + w(\rho)), v_0) - ((k^2n - \rho_0)(v_0 + w(\rho_0)), v_0) \\ &= -(\rho - \rho_0) \|v_0\|_{L^2(\Omega_b)}^2 + k^2(n(w(\rho) - w(\rho_0)), v_0) - (\rho - \rho_0)(w(\rho_0), v_0) \\ &\quad - (\rho - \rho_0)(w(\rho) - w(\rho_0), v_0) - \rho_0(w(\rho) - w(\rho_0), v_0) \end{aligned}$$

Thus, using (3.11) we have

$$\begin{aligned} 4\pi(T(\rho)v_0, v_0) &= (\rho - \rho_0) \left( - \|v_0\|_{L^2(\Omega_b)}^2 + ((k^2n - \rho_0)w', v_0) \right. \\ &\quad \left. - (w_0, v_0) + (\rho - \rho_0)\eta(\rho) \right) \end{aligned}$$

where  $\eta(\rho) = (k^2n\tilde{w}(\rho) - w' - \rho_0\tilde{w}(\rho) - (\rho - \rho_0)\tilde{w}(\rho), v_0)_{L^2(\Omega_b)}$  and  $|\eta(\rho)| \leq C\|v_0\|_{L^2(\Omega_b)}^2$  with  
 $C > 0$  independent of  $\rho$  sufficiently close to  $\rho_0$ .

We recall that  $w_0 \in H_0^2(\Omega_b)$  and satisfies  $\Delta w_0 + k^2 n w_0 = -(k^2 n - \rho_0)v_0$ . This allows us to write, since  $n$  and  $\rho$  are real

$$\begin{aligned} ((k^2 n - \rho_0)w', v_0) &= (w', (k^2 n - \rho_0)v_0) = -(w', \Delta w_0 + k^2 n w_0) \\ &= -(\Delta w' + k^2 n w', w_0) = -(v_0, w_0) \end{aligned}$$

Thus, we obtain,

$$\begin{aligned} 4\pi(T(\rho)v_0, v_0)_{L^2(\Omega_b)} &= (\rho - \rho_0) \left( -\|v_0\|_{L^2(\Omega_b)}^2 - (v_0, w_0) - (w_0, v_0) \right) \\ &\quad + (\rho - \rho_0)^2 \eta(\rho) \end{aligned}$$

1 which is exactly the identity (3.9) of the proposition. □

2 **Proposition 9.** Let  $\rho_0$  be a MTE of (2.14) and  $(v_0, w_0) \in L^2(\Omega_b) \times V_0(\Omega_b)$  an associated  
3 eigenpair. Then

$$(T(\rho)v(\rho), v(\rho)) = \frac{-1}{4\pi}(\rho - \rho_0) \|v_0\|_{L^2(\Omega_b)}^2 + (\rho - \rho_0)^2 \xi(\rho), \quad (3.14)$$

4 where  $v(\rho) = P(\rho)v_0$  and  $|\xi(\rho)| \leq C$  with  $C > 0$  independent from  $\rho$  sufficiently close to  $\rho_0$ .

*Proof.* We hereafter denote by  $O((\rho - \rho_0)^m)$  any quantity of the form  $(\rho - \rho_0)^m \xi(\rho)$  where  $\xi(\rho)$  is as in the proposition. We consider the following obvious splitting,

$$\begin{aligned} (T(\rho)v(\rho), v(\rho)) &= (T(\rho)v_0, v_0) + (T(\rho)v_0, (v(\rho) - v_0)) + (T(\rho)(v(\rho) - v_0), v_0) \\ &\quad + (T(\rho)(v(\rho) - v_0), (v(\rho) - v_0)) \end{aligned} \quad (3.15)$$

5 and separately analyze each of the terms appearing on the right hand side. From Lemma 4  
6 applied to  $g = v_0$  and using  $P(\rho_0)v_0 = v_0$  and  $\hat{w}(\rho_0) = 0$ , we have

$$v(\rho) - v_0 = -(\rho - \rho_0)(\Delta + \rho_0)\hat{w}'(\rho_0) + (\rho - \rho_0)^2 \mu(\rho) \quad (3.16)$$

7 where  $\hat{w}'(\rho_0) \in V_0(\Omega_b)$  satisfies

$$(\Delta + \rho_0)(\Delta + \rho_0)\hat{w}'(\rho_0) = v_0 \quad \text{in } \Omega_b \quad (3.17)$$

8 and  $\mu(\rho)$  is such that  $\|\mu(\rho)\|_{L^2(\Omega_b)} \leq C\|v_0\|_{L^2(\Omega_b)}$  with  $C > 0$  independent from  $\rho \in ]\rho_0 -$   
9  $\varepsilon, \rho_0 + \varepsilon[$  for some sufficiently small  $\varepsilon > 0$ . Let  $w'$  be the derivative of  $w$  at  $\rho = \rho_0$  defined  
10 in (3.11). Using definition (2.16) of the operator  $T(\rho)$  and expansion (3.16), we obtain

$$4\pi(T(\rho)v_0, (v(\rho) - v_0)) = ((k^2 n - \rho)(v_0 + w(\rho)), -(\rho - \rho_0)(\Delta + \rho_0)\hat{w}'(\rho_0) + O((\rho - \rho_0)^2)).$$

11

$$= (\rho - \rho_0)((\Delta + \rho)w(\rho), (\Delta + \rho_0)\hat{w}'(\rho_0)) + O((\rho - \rho_0)^2)$$

where we used the equation satisfied by  $w(\rho)$  in (2.11). We observe that

$$(\Delta + \rho)w(\rho) = (\Delta + \rho_0)w_0 + \Theta(\rho)$$

1 where  $\Theta(\rho) := (\Delta + \rho)(w(\rho) - w(\rho_0)) + (\rho - \rho_0)w_0$ . Using (3.11) we obtain that  $\|\Theta(\rho)\|_{L^2(\Omega_b)} =$   
2  $O((\rho - \rho_0))$  and therefore

$$4\pi(T(\rho)v_0, (v(\rho) - v_0)) = (\rho - \rho_0)((\Delta + \rho_0)w_0, (\Delta + \rho_0)\hat{w}'(\rho_0)) + O((\rho - \rho_0)^2)$$

3 Using (3.17) and the fact that  $w_0 \in V_0(\Omega_b)$  we end up with

$$4\pi(T(\rho)v_0, (v(\rho) - v_0)) = (\rho - \rho_0)(w_0, v_0) + O((\rho - \rho_0)^2). \quad (3.18)$$

4 Since  $\rho_0$  and  $n$  are real, if  $(v_0, w_0)$  solves (2.14) then  $(\overline{v_0}, \overline{w_0})$  solves (2.14) and therefore we  
5 can suppose without loss of generality that  $v_0$  and  $w_0$  are real valued. Using Lemma 2, we  
6 then deduce that

$$(T(\rho)(v(\rho) - v_0), v_0) = (T(\rho)v_0, (v(\rho) - v_0)). \quad (3.19)$$

7 The desired result follows from expression (3.15) by substituting (3.19) and (3.18) and using  
8 Proposition 6. □

10 We are now ready to state and prove the main result that provides a necessary and  
11 sufficient condition for an isolated MTE (i.e. MTE for which there exists a neighborhood in  
12  $\mathbb{R}$  where it is the only MTE).

13 **Theorem 10.** *Let  $\rho_0 \in \mathbb{R}$  and  $\delta_*(\rho)$  defined by (3.1) for  $\rho$  not being a MTE. Then we have*  
14 *the following equivalences.*

- 15 1. *Assume  $k^2n - \rho_0 \geq \alpha > 0$  in  $\Omega_b$ . Then  $\rho_0$  is an isolated MTE if and only if*  
16  $\lim_{\rho \searrow \rho_0} \delta_*(\rho) = 2\pi$ .
- 17 2. *Assume that we have  $\rho_0 - k^2n \geq \alpha > 0$  in  $\Omega_b$ . Then  $\rho_0$  is an isolated MTE if and only*  
18 *if  $\lim_{\rho \nearrow \rho_0} \delta_*(\rho) = 0$ .*

19 *Proof.* Let us consider the case  $k^2n - \rho_0 \geq \alpha > 0$  in  $\Omega_b$ . Let  $\rho_0$  be a MTE of (2.14) and  
20  $(v_0, w_0) \in L^2(\Omega_b) \times V_0(\Omega_b)$  a corresponding eigenpair. According to Proposition 9, we have

$$\cot \frac{\delta_*(\rho)}{2} = \inf_{\varphi \in \mathbb{H}_{\text{inc}}(\rho)} \frac{\Re(T(\rho)\varphi, \varphi)}{\Im(T(\rho)\varphi, \varphi)} \leq \frac{\Re(T(\rho)v_0, v_0)}{\Im(T(\rho)v_0, v_0)}.$$

21 As we have  $\Im(T(\rho)v_0, v_0) > 0$  if  $\rho$  is not a MTE, then we obtain

$$\frac{\Re(T(\rho)v_0(\rho), v_0(\rho))}{\Im(T(\rho)v_0(\rho), v_0(\rho))} = \frac{\frac{-1}{4\pi} \|v_0\|_{L^2(\Omega_b)}^2 + (\rho - \rho_0)\Re \eta(\rho)}{(\rho - \rho_0)\Im \eta(\rho)} \xrightarrow{\rho \searrow \rho_0} -\infty$$

22 and we conclude that  $\lim_{\rho \searrow \rho_0} \delta_*(\rho) = 2\pi$ . The case  $\rho_0 - k^2n \geq \alpha > 0$  in  $\Omega_b$  can be proved  
23 similarly. These provide the necessary conditions that complement Theorem 6 and end the  
24 proof of this theorem. □

## 4 Numerical experiments and validation

The goal of this section is to illustrate the theoretical results of Theorem 10 with synthetic 2D numerical examples. It also aims at testing the precision and the stability of the underlying numerical scheme to retrieve modified transmission eigenvalues. When the geometry is circular, one can derive an analytical expression of the modified scattering operator  $\mathcal{S}$  and characterize the MTEs as the zeros of some determinant that can be computed using standard routines (for instance the ones implemented in NumPy). For the other geometries we numerically approximate the far field operators  $F$  and  $F_b$  and the operators  $S$  and  $S_b$  using FreeFem++ finite elements library [13].

### 4.1 Validation in the case where the domain $\Omega$ is a disc

In this first example we consider a case where analytical expressions can be derived. We take  $n$  equal to a real constant in  $\Omega = B_R$  and  $n = 1$  in  $\mathbb{R}^2 \setminus \bar{\Omega}$  where  $B_R$  is the ball of radius  $R$  centred at the origin. Moreover, for the modified background in (2.7), we take  $\Omega_b = \Omega$ . Let us recall that in 2D, in order to have unitary operators,  $S$  and  $S^b$  are respectively defined from  $F$  and  $F^b$  by

$$S := \text{Id} + 2ik \frac{e^{-i\pi/4}}{\sqrt{8\pi k}} F \quad \text{and} \quad S^b := \text{Id} + 2ik \frac{e^{-i\pi/4}}{\sqrt{8\pi k}} F^b.$$

Following [3], the non zero eigenvalues of  $\mathcal{F}(\rho) = (S_b(\rho))^* F^m(\rho)$  coincide with the set  $\{\gamma_m; m \in \mathbb{Z}\}$ , with

$$\gamma_m := (1 + 2\overline{D_{b,m}})(1 + 2D_m).$$

where

$$D_{b,m} := \frac{-\sqrt{\rho} J'_m(\sqrt{\rho}R) J_m(kR) + k J'_m(kR) J_m(\sqrt{\rho}R)}{-k J_m(\sqrt{\rho}R) H_m^{(1)'}(kR) + \sqrt{\rho} J'_m(\sqrt{\rho}R) H_m^{(1)}(kR)}$$

$$D_m := \frac{-\sqrt{n} J'_m(k\sqrt{n}R) J_m(kR) + J'_m(kR) J_m(k\sqrt{n}R)}{-J_m(k\sqrt{n}R) H_m^{(1)'}(kR) + \sqrt{n} J'_m(k\sqrt{n}R) H_m^{(1)}(kR)}$$

and  $J_m$  and  $H_m^{(1)}$  stand for the Bessel and Hankel functions of the first kind of order  $m$ . We denote by  $\hat{\delta}_m \in [0; 2\pi)$  the phase of the  $\gamma_m$ .

Figure 4.1 displays the curves  $\rho \mapsto \hat{\delta}_m(\rho) \in [0, 2\pi)$  for  $\rho \in (1, 40)$  for  $n = 4$ ,  $k = 5$  and  $R = 2\pi/k$ . Each colour corresponds to a different value of  $m \in \{0, \dots, 35\}$ . The vertical dashed lines indicates the MTEs computed as the zeros of the determinant

$$\det \begin{pmatrix} J_m(\sqrt{\rho}R) & J_m(k\sqrt{n}R) \\ \sqrt{\rho} J'_m(\sqrt{\rho}R) & k\sqrt{n} J'_m(k\sqrt{n}R) \end{pmatrix} \quad (4.1)$$

that characterizes the existence of non trivial solutions to (2.14) using separation of variables. For  $\rho \in [1, 40[$ ,  $k^2 n - \rho > 0$  and we indeed observe in Figure 4.1 that there exists  $m_0$  such

- 1 that the phase  $\rho \mapsto \hat{\delta}_{m_0}(\rho)$  goes to  $2\pi$  as  $\rho \searrow \rho_0$  where  $\rho_0$  is an MTE. For  $\rho$  sufficiently close  
 2 to  $\rho_0$  the  $\hat{\delta}_{m_0}(\rho)$  coincides with the  $\delta_*(\rho)$  of Theorem 10.

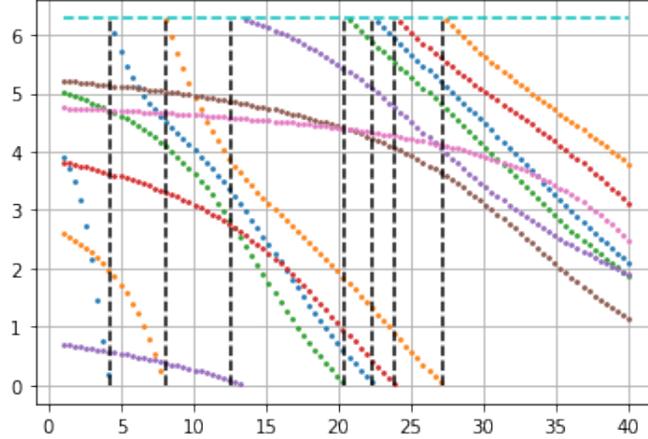


Figure 4.1: The curves  $\rho \mapsto \hat{\delta}_m(\rho) \in [0, 2\pi)$  for  $\rho \in (1, 40)$  in the case where  $\Omega = \Omega_b = B_R$ ,  $n = 4$ ,  $k = 5$  and  $R = 2\pi/k$ . Each colour corresponds to a different value of  $m \in \{0, \dots, 7\}$ . The vertical dashed lines indicate the MTEs computed as the zeros of (4.1).

### 3 4.2 Numerical validation for other geometries

4 We here rely on the finite elements library **FreeFem++** [13] to numerically solve the scattering  
 5 problem and synthetically generate  $F_b$ ,  $F$ ,  $S$  and  $S_b$  for a given geometry and set of physical  
 6 parameters. We use  $M$  uniformly distributed incident directions  $d_j = (\cos(\theta_j), \sin(\theta_j))$ ,  
 7  $\theta_j = j2\pi/M$ ,  $j = 0, \dots, M-1$  and numerically evaluate the far fields at  $\hat{x}_i = (\cos(\theta_i), \sin(\theta_i))$ ,  
 8  $i = 0, \dots, M-1$ . This gives for instance an  $M \times M$  matrix  $F$  whose entries are  $F_{i,j} =$   
 9  $u_\infty(\hat{x}_i, d_j)$ . Similar procedure holds for  $F_b$ . In all numerical examples we take  $M = 35$ .

10 After generating the matrices  $F$  and  $F_b$  we use Python to evaluate the eigenvalues of  
 11  $\mathcal{F}(\rho)$  and display the curves  $\rho \mapsto \delta_m(\rho)$ . Note that the index  $m$  here has a different  
 12 meaning than in the case of the disc above. It corresponds to the index of the eigenvalues  
 13 generated by the eigenvalue solver, which has nothing to do with the index of the Fourier  
 14 mode in the case of the disc.

15 In order to validate the identified MTEs by the inside-outside algorithm, we numerically  
 16 evaluate the MTEs by solving the eigenvalue problem (2.14). For that purpose we use a  
 17  $H^1$ -variational formulation of the problem (as in [11]). Multiplying the second equation by  
 18  $w' \in H_0^1(\Omega_b)$  and the first equation by  $v' \in H^1(\Omega_b)$ , we obtain after integration by parts and  
 19 using that the normal derivative of  $w$  vanishes on  $\partial\Omega_b$

$$\begin{cases} \int_{\Omega_b} (\nabla w \nabla v' + k^2 n w v') dx = \int_{\Omega_b} (\rho - k^2 n) v v' dx, \\ \int_{\Omega_b} (\nabla v \nabla w' + \rho v w') dx = 0, \end{cases} \quad (4.2)$$

1 for all  $(w', v') \in H_0^1(\Omega_b) \times H^1(\Omega_b)$ . This eigenvalue problem is discretized for  $(w, v) \in H_0^1(\Omega_b) \times$   
2  $H^1(\Omega_b)$  using  $P_1$  Lagrange finite elements with the help of `FreeFem++` [13]. The discrete  
3 eigenvalue problem is then solved using the package `PETSc` embedded in `FreeFem++`. Since  
4 we relaxed the condition on the normal trace of  $w$ , we observed that some spurious numerical  
5 eigenvalues may show up. They correspond to eigenfunctions that do not have vanishing  
6 normal derivative for  $w$  on  $\partial\Omega_b$ . These spurious modes are discarded by checking whether  
7 the latter property is verified or not.

8 We first validate the procedure in the case of the disc for which the numerical results  
9 have already been obtained above using analytical expression of the solutions. Figure 4.4-  
10 left shows the obtained results in the case of the experiment illustrated by Figure 4.1. We  
11 observe that we obtain the same results. In order to verify the stability of the inside outside  
12 duality method with respect to noise, we repeat the experiment by adding a random noise  
13 to the far field operator  $F$ . More specifically, we replace each entry  $F_{i,j}$  of the far field with  
14  $\tilde{F}_{i,j} := (1 + \eta_{i,j})F_{i,j}$  where  $\eta_{i,j} \in \mathbb{C}$  has a real and imaginary values randomly drawn between  
15  $-\epsilon$  and  $\epsilon > 0$ . Figure 4.4-right displays the obtained results for  $\epsilon = 2\%$ .

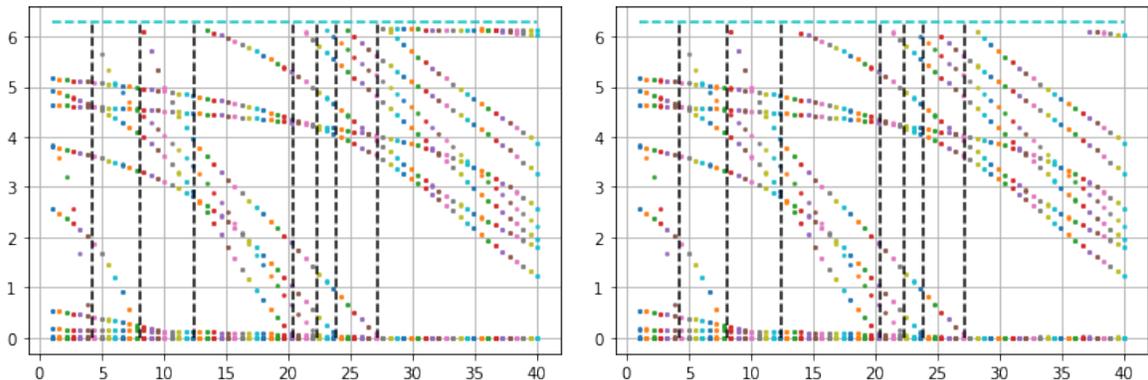


Figure 4.2: The two figures display the curves  $\rho \mapsto \delta_m(\rho) \in [0, 2\pi)$  for  $\rho \in (1, 40)$  in the case where  $\Omega = \Omega_b = B_R$ ,  $n = 4$ ,  $k = 5$  and  $R = 2\pi/k$ . This corresponds to the same experiment as in Figure 4.1 but using finite elements method to numerically evaluate the far fields and MTEs. The vertical dashed lines correspond to the numerical MTEs obtained by solving (4.2). Figure on the left is obtained with far field without added random noise. The figure on the right is obtained with noisy far field with noise level  $\epsilon = 2\%$ .

16 The following examples are for other simple geometries. The first two are convex domains  
17 shown in Figure 4.3. The associate spectrum is relatively simple and the inside outside  
18 duality is able to correctly identify the MTEs as attested by Figure 4.4.

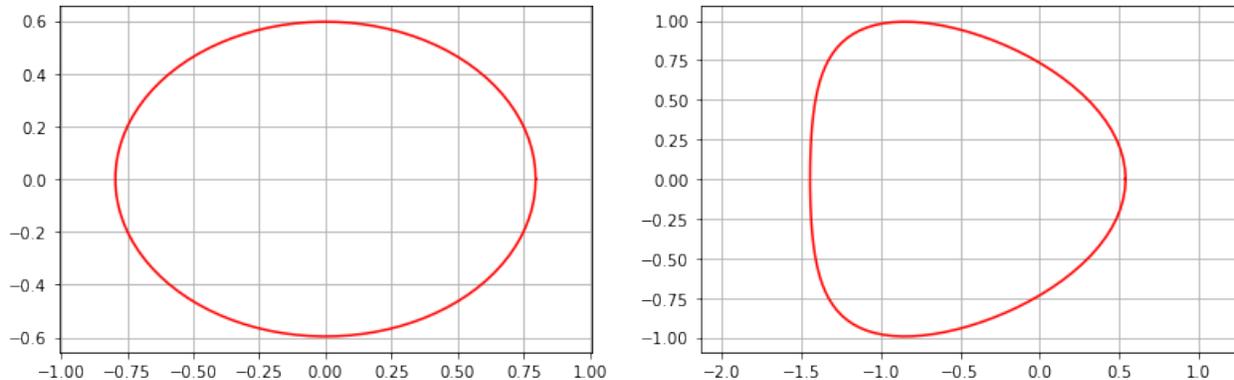


Figure 4.3: Geometry of the convex domains for our experiments

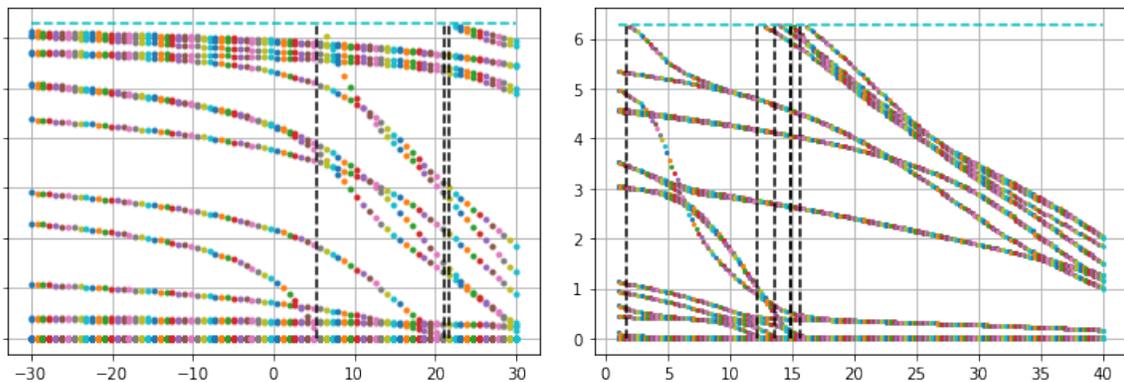


Figure 4.4: The left and right figures display the curves  $\rho \mapsto \delta_m(\rho) \in [0, 2\pi)$  for  $\rho \in (1, 40)$  in the case where  $n = 2$ ,  $k = 5$  and the domains  $\Omega = \Omega_b$  are respectively shown in Figure 4.3 left and right. The vertical dashed lines correspond to the numerical MTEs obtained by solving (4.2). The far fields are corrupted with a noise level  $\epsilon = 2\%$ .

1 In the last two examples we consider non convex domains having the shape of a kite as  
 2 shown in Figure 4.5. For these domains, we observe that the number of MTEs is higher in  
 3 the same interval as for the previous geometries as shown in Figure 4.6 that corresponds  
 4 to noise free far field operators. The MTEs are correctly identified but the higher is the  
 5 concavity the lesser is the precision, especially for closely separated eigenvalues. Figure 4.7  
 6 corresponds with noisy far field operators with noise level  $\epsilon = 2\%$ . For these examples, it  
 7 seems difficult to identify the exact values of MTEs. One should then be cautious when  
 8 exploiting the MTEs in solutions to inverse problems: precise values maybe out of reach  
 9 using the inside outside duality for non convex geometries. Comparing Figures 4.6 and 4.7  
 10 we observe that the overall behaviour of the spectrum of the far field operator is relatively  
 11 stably reproduced in the case of noisy operators. Consequently, if only qualitative behaviour  
 12 of these quantities is of interest (as for instance for the inversion method developed in [1]),

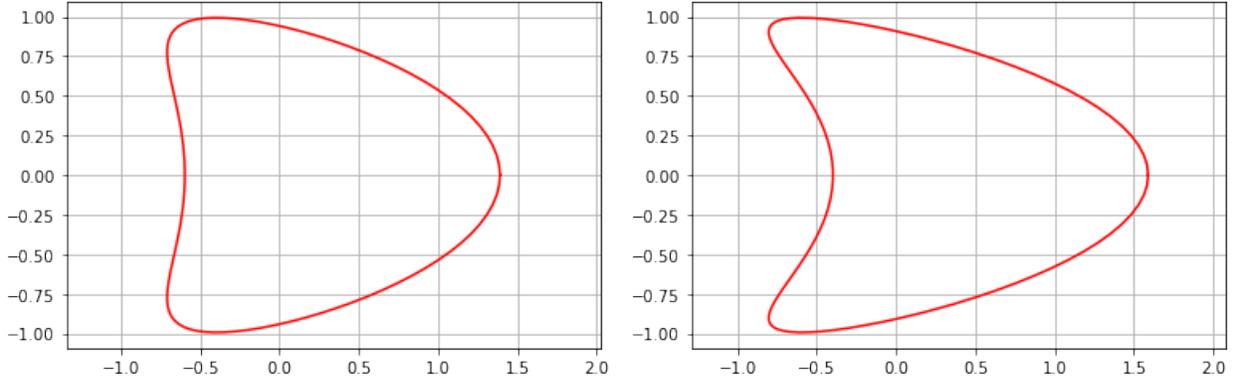


Figure 4.5: The examples of non convex domains with different concavity.

1 then the use of the inside outside duality can be useful. For further discussions on the  
numerical implementation/accuracy of the inside outside duality, we refer to [14].

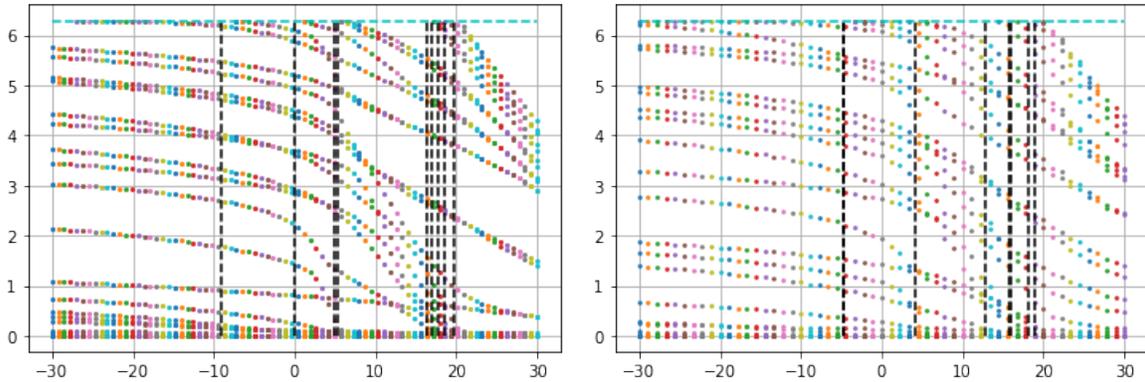


Figure 4.6: The left and right figures display the curves  $\rho \mapsto \delta_m(\rho) \in [0, 2\pi)$  for  $\rho \in (1, 40)$   
in the case where  $n = 2$ ,  $k = 5$  and the domains  $\Omega = \Omega_b$  are respectively shown in Figure  
4.5 left and right. The vertical dashed lines correspond to the numerical MTEs obtained by  
solving (4.2).

2

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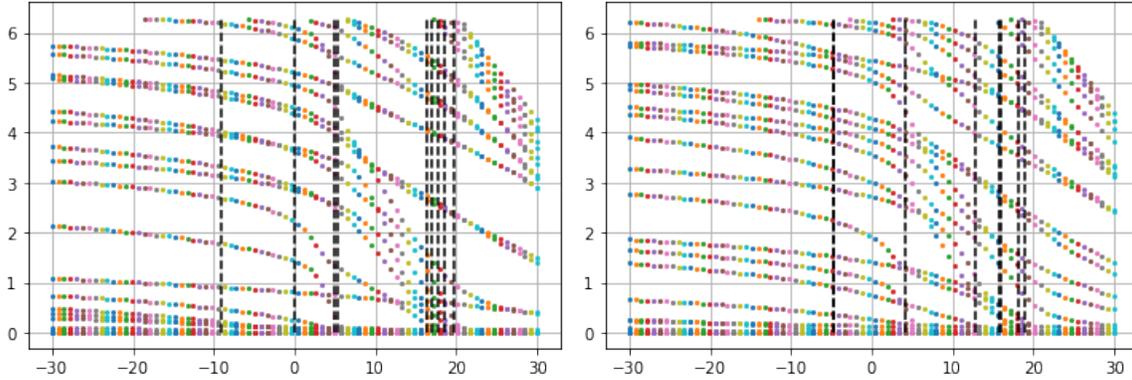


Figure 4.7: The left and right figures display the curves  $\rho \mapsto \delta_m(\rho) \in [0, 2\pi)$  for  $\rho \in (1, 40)$  in the case where  $n = 2$ ,  $k = 5$  and the domains  $\Omega = \Omega_b$  are respectively shown in Figure 4.5 left and right. The vertical dashed lines correspond to the numerical MTEs obtained by solving (4.2). The far fields are corrupted with a noise level  $\epsilon = 2\%$ .

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