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**Weighted Radon transforms for which  
the Chang approximate inversion formula is precise  
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**Abstract.** We describe all weighted Radon transforms on the plane for which the Chang approximate inversion formula is precise. Some subsequent results, including the Cormack type inversion for these transforms, are also given.

**1. Introduction**

We consider the weighted ray transformation  $P_W$  defined by the formula

$$P_W f(s, \theta) = \int_{\mathbb{R}} W(s\theta^\perp + t\theta, \theta) f(s\theta^\perp + t\theta) dt, \quad (1)$$

$$s \in \mathbb{R}, \theta = (\theta_1, \theta_2) \in \mathbb{S}^1, \theta^\perp = (-\theta_2, \theta_1),$$

where  $W = W(x, \theta)$  is the weight,  $f = f(x)$  is a test function,  $x \in \mathbb{R}$ ,  $\theta \in \mathbb{S}^1$ . Up to change of variables,  $P_W$  is known also as weighted Radon transform on the plane.

We recall that in definition (1) the product  $\mathbb{R} \times \mathbb{S}^1$  is interpreted as the set of all oriented straight lines in  $\mathbb{R}^2$ . If  $\gamma = (s, \theta) \in \mathbb{R} \times \mathbb{S}^1$ , then  $\gamma = \{x \in \mathbb{R}^2 : x = s\theta^\perp + t\theta, t \in \mathbb{R}\}$  (modulo orientation) and  $\theta$  gives the orientation of  $\gamma$ .

We assume that

$$\begin{aligned} W & \text{ is complex - valued,} \\ W & \in C(\mathbb{R}^2 \times \mathbb{S}^1) \cap L^\infty(\mathbb{R}^2 \cap \mathbb{S}^1), \\ w_0(x) & \stackrel{\text{def}}{=} \frac{1}{2\pi} \int_{\mathbb{S}^1} W(x, \theta) d\theta \neq 0, \quad x \in \mathbb{R}^2, \end{aligned} \quad (2)$$

where  $d\theta$  is the standard element of arc length on  $\mathbb{S}^1$ .

If  $W \equiv 1$ , then  $P_W$  is known as the classical ray (or Radon) transform on the plane. If

$$\begin{aligned} W(x, \theta) &= \exp(-Da(x, \theta)), \\ Da(x, \theta) &= \int_0^{+\infty} a(x + t\theta) dt, \end{aligned} \quad (3)$$

where  $a$  is a complex-valued sufficiently regular function on  $\mathbb{R}^2$  with sufficient decay at infinity, then  $P_W$  is known as the attenuated ray (or Radon) transform.

The classical Radon transform arises, in particular, in the X-ray transmission tomography. The attenuated Radon transform (at least, with  $a \geq 0$ ) arises, in particular, in the

single photon emission computed tomography (SPECT). Some other weights  $W$  also arise in applications. For more information in this connection see, for example, [Na], [K].

Precise and simultaneously explicit inversion formulas for the classical and attenuated Radon transforms were given for the first time in [R] and [No], respectively. For some other weights  $W$  precise and simultaneously explicit inversion formulas were given in [B], [G].

On the other hand, the following Chang approximate inversion formula for  $P_W$ , where  $W$  is given by (3) with  $a \geq 0$ , is used for a long time, see [Ch], [M], [K]:

$$\begin{aligned} f_{appr}(x) &= \frac{1}{4\pi w_0(x)} \int_{\mathbb{S}^1} h'(x\theta^\perp, \theta) d\theta, \quad h'(s, \theta) = \frac{d}{ds} h(s, \theta), \\ h(s, \theta) &= \frac{1}{\pi} p.v. \int_{\mathbb{R}} \frac{P_W f(t, \theta)}{s-t} dt, \quad s \in \mathbb{R}, \theta \in \mathbb{S}^1, x \in \mathbb{R}^2, \end{aligned} \tag{4}$$

where  $w_0$  is defined in (2). It is known that (4) is efficient as the first approximation in SPECT reconstructions and, in particular, is sufficiently stable to the strong Poisson noise of SPECT data. The results of the present note consist of the following:

- (1) In Theorem, under assumptions (2), we describe all weights  $W$  for which the Chang approximate inversion formula (4) is precise, that is  $f_{appr} \equiv f$  on  $\mathbb{R}^2$ ;
- (2) For  $P_W$  with  $W$  of Theorem we give also the Cormack type inversion (see Remark A) and inversion from limited angle data (see Remark B).

These results are presented in detail in the next section. In addition, we give also an explanation of efficiency of the Chang formula (4) as the first approximation in SPECT reconstructions (on the level of integral geometry).

## 2. Results

Let

$$C_0(\mathbb{R}^2) \text{ denote the space of continuous compactly supported functions on } \mathbb{R}^2. \tag{5}$$

Let

$$\begin{aligned} L^{\infty, \sigma}(\mathbb{R}^2) &= \{f : M^\sigma f \in L^\infty(\mathbb{R}^2)\}, \\ M^\sigma f(x) &= (1 + |x|)^\sigma f(x), \quad x \in \mathbb{R}^2, \quad \sigma \geq 0. \end{aligned} \tag{6}$$

**Theorem.** *Let assumptions (2) hold and let  $f_{appr}(x)$  be given by (4). Then*

$$f_{appr} = f \text{ (in the sense of distributios) on } \mathbb{R}^2 \text{ for all } f \in C_0(\mathbb{R}^2) \tag{7}$$

*if and only if*

$$W(x, \theta) - w_0(x) \equiv w_0(x) - W(x, -\theta), \quad x \in \mathbb{R}^2, \quad \theta \in \mathbb{S}^1. \tag{8}$$

*(This result remains valid with  $C_0(\mathbb{R}^2)$  replaced by  $L^{\infty, \sigma}(\mathbb{R}^2)$  for  $\sigma > 1$ .)*

Theorem 1 is based on the following facts:

- Formula (4) coincides with the classical Radon inversion formula if  $W \equiv 1$  and, as a corollary, is precise if  $W \equiv w_0$ .
- Formula (4) is equivalent to the symmetrized formula

$$\begin{aligned}
f_{appr}(x) &= \frac{1}{4\pi w_0(x)} \int_{\mathbb{S}^1} g'(x\theta^\perp, \theta) d\theta, \quad x \in \mathbb{R}^2, \\
g(s, \theta) &= \frac{1}{2\pi} p.v. \int_{\mathbb{R}} \frac{P_W f(t, \theta) + P_W f(-t, -\theta)}{s - t} dt, \quad (s, \theta) \in \mathbb{R} \times \mathbb{S}^1.
\end{aligned} \tag{9}$$

- The following formula holds:

$$\begin{aligned}
\frac{1}{2}(P_W f(s, \theta) + P_W f(-s, -\theta)) &= P_{W_{sym}} f(s, \theta), \quad (s, \theta) \in \mathbb{R} \times \mathbb{S}^1, \\
W_{sym}(x, \theta) &= \frac{1}{2}(W(x, \theta) + W(x, -\theta)), \quad x \in \mathbb{R}^2, \quad \theta \in \mathbb{S}^1.
\end{aligned} \tag{10}$$

- If

$$\begin{aligned}
q &\in C(\mathbb{R} \times \mathbb{S}^1), \quad \text{supp } q \text{ is compact,} \quad q(s, \theta) = q(-s, -\theta), \\
g(s, \theta) &= \frac{1}{\pi} p.v. \int_{\mathbb{R}} \frac{q(t, \theta)}{s - t} dt, \quad (s, \theta) \in \mathbb{R} \times \mathbb{S}^1, \\
\int_{\mathbb{S}^1} g'(x\theta^\perp, \theta) d\theta &\equiv 0 \quad \text{as a distribution of } x \in \mathbb{R}^2,
\end{aligned} \tag{11}$$

then  $q \equiv 0$  on  $\mathbb{R} \times \mathbb{S}^1$ .

The statement that, under the assumptions of Theorem, property (8) implies (7) can be also deduced from considerations developed in [K].

Using that  $W_{sym} \equiv w_0$  under condition (8), we obtain also the following

**Remarks.** Let conditions (2), (8) be fulfilled. Let  $f \in C_0(\mathbb{R}^2)$ . Then:

- $P_W f$  on  $\Omega(D)$  uniquely determines  $f$  (or more precisely  $w_0 f$ ) on  $\mathbb{R}^2 \setminus D$  via (10) and the Cornack inversion from  $P_{W_{sym}} f$  on  $\Omega(D)$ , where  $D$  is a compact in  $\mathbb{R}^2$ ,  $\Omega(D)$  denotes the set of all straight lines in  $\mathbb{R}^2$  which do not intersect  $D$ ;
- $P_W f$  on  $\mathbb{R} \times (S_+ \cup S_-)$  uniquely determines  $f$  on  $\mathbb{R}^2$  via (10) and standard inversion from the limited angle data  $P_{W_{sym}} f$  on  $\mathbb{R} \times S_+$ , where  $S_+$  is an arbitrary nonempty open connected subset of  $\mathbb{S}^1$ ,  $S_- = -S_+$ .

For the case when  $W$  is given by (3) under the additional conditions that  $a \geq 0$  and  $\text{supp } a \subset D$ , where  $D$  is some known bounded domain which is not too big, and for  $f \in C(\mathbb{R}^2)$ ,  $f \geq 0$ ,  $\text{supp } f \subset D$ , the transform  $P_W f$  is relatively well approximated by  $P_{W_{appr}} f$ , where  $W_{appr}(x, \theta) = w_0(x) + (1/2)(W(x, \theta) - W(x, -\theta))$ . In addition, this  $W_{appr}$  already satisfies (8). This explains the efficiency of (4) as the first approximation in SPECT reconstructions (on the level of integral geometry).

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