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A CHARACTERIZATION OF MODULATION SPACES BY SYMPLECTIC ROTATIONS

ELENA CORDERO, MAURICE DE GOSSON, AND FABIO NICOLA

ABSTRACT. This note contains a new characterization of modulation spaces $M_m^p(\mathbb{R}^n)$, $1 \leq p \leq \infty$, by symplectic rotations. Precisely, instead to measure the time-frequency content of a function by using translations and modulations of a fixed window as building blocks, we use translations and metaplectic operators corresponding to symplectic rotations. Technically, this amounts to replace, in the computation of the $M_m^p(\mathbb{R}^n)$ -norm, the integral in the time-frequency plane with an integral on $\mathbb{R}^n \times U(2n, \mathbb{R})$ with respect to a suitable measure, $U(2n, \mathbb{R})$ being the group of symplectic rotations. More conceptually, we are considering a sort of polar coordinates in the time-frequency plane. To have invariance under symplectic rotations we choose a Gaussian as suitable window function. We also provide a similar (and easier) characterization with the group $U(2n, \mathbb{R})$ being reduced to the *n*-dimensional torus \mathbb{T}^n .

1. INTRODUCTION

The objective of this study is to find a new characterization of modulation spaces using symplectic rotations. Precisely, we are interested in those metaplectic operators $\widehat{S} \in Mp(n, \mathbb{R})$, such that the corresponding projection $S := \pi(\widehat{S})$ onto the symplectic group $Sp(n, \mathbb{R})$ is a symplectic rotation. Let us recall that the symplectic group $Sp(n, \mathbb{R})$ is the subgroup of $2n \times 2n$ invertible matrices $GL(2n, \mathbb{R})$, defined by

(1)
$$Sp(n,\mathbb{R}) = \left\{ S \in GL(2n,\mathbb{R}) : SJS^T = J \right\},$$

where J is the orthogonal matrix

$$J = \begin{pmatrix} 0_n & I_n \\ -I_n & 0_n \end{pmatrix},$$

 $(I_n, 0_n \text{ are the } n \times n \text{ identity matrix and null matrix, respectively})$. Here we consider the subgroup

$$U(2n,\mathbb{R}) := Sp(n,\mathbb{R}) \cap O(2n,\mathbb{R}) \simeq U(n)$$

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of symplectic rotations (cf., e.g. [15, Section 2.3]), namely

(2)
$$U(2n,\mathbb{R}) = \left\{ \begin{pmatrix} A & -B \\ B & A \end{pmatrix} : AA^T + BB^T = I_n, AB^T = B^T A \right\} \subset Sp(n,\mathbb{R}),$$

endowed with the normalized Haar measure dS (the group $U(2n, \mathbb{R})$, being compact, is unimodular).

In the 80's H. Feichtinger [16] introduced modulation spaces to measure the time-frequency concentration of a function/distribution on the time-frequency space (or phase space) \mathbb{R}^{2n} . They are nowadays become popular among mathematicians and engineers because they have found numerous applications in signal processing [6, 19, 20], pseudodifferential and Fourier integral operators [7, 8, 9, 28, 29], partial differential equations [1, 2, 3, 4, 10, 13, 11, 11, 32, 33, 34] and quantum mechanics [12, 15].

To recall their definition, we need a few time-frequency tools. First, the translation T_x and modulation M_{ξ} operators are defined by

$$T_x f(t) = f(t-x), \quad M_{\xi} f(t) = e^{2\pi i t \cdot \xi} f(t), \quad t, x, \xi \in \mathbb{R}^n,$$

for any function f on \mathbb{R}^n .

The time-frequency representation which occurs in the definition of modulation spaces is the short-time Fourier Transform (STFT) of a distribution $f \in \mathcal{S}'(\mathbb{R}^n)$ with respect to a function $g \in \mathcal{S}(\mathbb{R}^n) \setminus \{0\}$ (so-called window), given by

(3)
$$V_g f(x,\xi) = \langle f, M_\xi T_x g \rangle = \int_{\mathbb{R}^n} f(t) \overline{g(t-x)} e^{-2\pi i t \cdot \xi} dt, \quad x,\xi \in \mathbb{R}^n.$$

The short-time Fourier transform is well-defined whenever the bracket $\langle \cdot, \cdot \rangle$ makes sense for dual pairs of function or distribution spaces, in particular for $f \in \mathcal{S}'(\mathbb{R}^n)$, $g \in \mathcal{S}(\mathbb{R}^n)$, or for $f, g \in L^2(\mathbb{R}^n)$.

Let $m(x,\xi)$ be a continuous weight, v-moderate for some submultiplicative weight v (see [22, Section 11.1] for details - we will not use explicitly these properties). We also assume that m has at most polynomial growth.

Definition 1.1 (Modulation spaces). Given $g \in \mathcal{S}(\mathbb{R}^n)$, and $1 \leq p \leq \infty$, the modulation space $M_m^p(\mathbb{R}^n)$ consists of all tempered distributions $f \in \mathcal{S}'(\mathbb{R}^n)$ such that $V_g f \in L_m^p(\mathbb{R}^{2n})$. The norm on $M_m^p(\mathbb{R}^n)$ is

(4)
$$\|f\|_{M^p_m} = \|V_g f\|_{L^p_m} = \left(\int_{\mathbb{R}^{2n}} |V_g f(x,\xi)|^p m(x,\xi)^p dx d\xi\right)^{1/p}$$
$$= \left(\int_{\mathbb{R}^{2n}} |\langle f, M_\xi T_x g\rangle|^p m(x,\xi)^p dx d\xi\right)^{1/p}$$

(with obvious modifications for $p = \infty$).

The spaces $M_m^p(\mathbb{R}^n)$ are Banach spaces, and every nonzero $g \in M_v^1(\mathbb{R}^n)$ yields an equivalent norm in (4), so that their definition is independent of the choice of $g \in M_v^1(\mathbb{R}^n)$ (see [16, 22]).

We now provide an equivalent norm to (4) by using translations T_x (or modulations M_{ξ}) and the operators \widehat{S} , with $S \in U(2n, \mathbb{R})$ as follows.

Theorem 1.2. Consider the Gaussian function $\varphi(t) = 2^{d/4}e^{-\pi|t|^2}$. (i) For $1 \le p < \infty$ and $f \in M_m^p(\mathbb{R}^n)$, we have

(5)
$$||f||_{M^p_m(\mathbb{R}^n)} \asymp \left(\int_{\mathbb{R}^n \times U(2n,\mathbb{R})} |x|^n |\langle f, \widehat{S}T_x\varphi \rangle|^p m(S(x,0)^T)^p dx dS \right)^{\frac{1}{p}},$$

where dx is the Lebesgue measure on \mathbb{R}^n and dS the Haar measure on $U(2n, \mathbb{R})$. Similarly,

(6)
$$\|f\|_{M^p_m(\mathbb{R}^n)} \asymp \left(\int_{\mathbb{R}^n \times U(2n,\mathbb{R})} |\xi|^n |\langle f, \widehat{S}M_\xi\varphi\rangle|^p m(S(0,\xi)^T)^p d\xi dS \right)^{\frac{1}{p}},$$

with $d\xi$ being the Lebesgue measure on \mathbb{R}^n and dS the Haar measure on $U(2n, \mathbb{R})$. (ii) For $p = \infty$, $f \in M^{\infty}_m(\mathbb{R}^n)$, it occurs

(7)
$$\|f\|_{M_m^{\infty}(\mathbb{R}^n)} \asymp \sup_{S \in U(2n,\mathbb{R})} \sup_{x \in \mathbb{R}^n} |\langle f, \widehat{S}T_x \varphi \rangle | m(S(x,0)^T)$$

and, similarly,

(8)
$$||f||_{M_m^{\infty}(\mathbb{R}^n)} \asymp \sup_{S \in U(2n,\mathbb{R})} \sup_{\xi \in \mathbb{R}^n} |\langle f, \widehat{S}M_{\xi}\varphi \rangle| m(S(0,\xi)^T).$$

The interpretation of the integral (5) above is as follows. The metaplectic operator \hat{S} produces a time-frequency rotation of the shifted Gaussian $T_x\varphi$. In this way, the operator

$$f \mapsto \langle f, \widehat{S}T_x \varphi \rangle$$

detects the time-frequency content of f in an oblique strip, see Figure 1. All the contributions are then added together with a weight $|x|^n$ which takes into account the underlapping of the strips as $|x| \to +\infty$ and the overlapping as $x \to 0$.

Formulas (6), (7) and (8) have similar meanings.

Observe that in dimension n = 1, $U(2, \mathbb{R}) \simeq U(1)$ and the above formula is essentially a transition to polar coordinates with |x| being the Jacobian.

Comparing (4) and (5) we observe that in (5) the modulation operator M_{ξ} is replaced by the metaplectic operator \widehat{S} and the integral on the phase space \mathbb{R}^{2n} has become an integral on the cartesian product $\mathbb{R}^n \times U(2n, \mathbb{R})$. The integration parameters (x, ξ) of (4) live in \mathbb{R}^{2n} , with dim $\mathbb{R}^{2n} = 2n$, whereas the parameters (x, S) of (5) live in $\mathbb{R}^n \times U(2n, \mathbb{R})$. Recall that dim $U(2n, \mathbb{R}) = n^2$ [15]; this suggests that a formula similar to (5) should hold when $U(2n, \mathbb{R})$ is reduced to



FIGURE 1. The time-frequency content of f in the oblique strip is detected by the operator $f \mapsto \langle f, \widehat{S}T_x \varphi \rangle$.

a suitable subgroup $K \subset U(2n, \mathbb{R})$ of dimension n. This is indeed the case (and easier to see), as shown in the subsequent Theorem 1.3.

Consider the n-dimensional torus

(9)
$$\mathbb{T}^n = \left\{ S = \begin{pmatrix} e^{i\theta_1} & & \\ & \ddots & \\ & & e^{i\theta_n} \end{pmatrix} : \theta_1, \dots, \theta_n \in \mathbb{R} \right\} \subset U(n)$$

with the Haar measure $dS = d\theta_1 \dots d\theta_n$. The torus is isomorphic to a subgroup $K \subset U(2n, \mathbb{R})$, via the isomorphism ι in formula (16) below (see the subsequent section).

We exhibit the following characterization for M^p -spaces.

Theorem 1.3. Let φ be the Gaussian of Theorem 1.2. (i) For $1 \leq p < \infty$, $f \in M^p_m(\mathbb{R}^n)$, we have

(10)
$$\|f\|_{M^p_m(\mathbb{R}^n)} \asymp \left(\int_{\mathbb{R}^n \times \mathbb{T}^n} |x_1 \dots x_n| |\langle f, \widehat{S}T_x \varphi \rangle|^p m(S(x, 0)^T)^p dx dS \right)^{\frac{1}{p}},$$

and, similarly,

(11)
$$\|f\|_{M^p_m(\mathbb{R}^n)} \asymp \left(\int_{\mathbb{R}^n \times \mathbb{T}^n} |\xi_1 \dots \xi_n| |\langle f, \widehat{S}M_{\xi}\varphi \rangle|^p m(S(0,\xi)^T)^p d\xi dS \right)^{\frac{1}{p}}$$

(ii) For $p = \infty$,

(12)
$$||f||_{M_m^{\infty}(\mathbb{R}^n)} \asymp \sup_{S \in \mathbb{T}^n} \sup_{x \in \mathbb{R}^n} |\langle f, \widehat{S}T_x \varphi \rangle| m(S(x, 0)^T)$$

and

(13)
$$||f||_{M_m^{\infty}(\mathbb{R}^n)} \asymp \sup_{S \in \mathbb{T}^n} \sup_{\xi \in \mathbb{R}^n} |\langle f, \widehat{S}M_{\xi}\varphi \rangle| m(S(0,\xi)^T).$$

The above results for the groups $U(2n, \mathbb{R})$ and \mathbb{T}^n can be interpreted, in a sense, as two extreme cases, and it would be interesting to find, more generally, for which compact subgroups $K \subset U(2n, \mathbb{R})$ similar characterizations hold. We conjecture that they should be precisely the subgroups $K \subset U(2n, \mathbb{R})$ such that every orbit for their action on \mathbb{R}^{2n} intersects $\{0\} \times \mathbb{R}^n$ (up to subsets of measure zero), with a corresponding weighted measure on $\mathbb{R}^n \times K$ to be determined.

Another problem which is worth investigating is the study of discrete versions of the above characterizations via coorbit theory [17].

The paper is organized as follows: in Section 2 we collected some preliminary results, whereas Section 3 is devoted to the proof of Theorems 1.2 and 1.3. In Section 4 we rephrase more explicitly Theorem 1.3 in terms of the partial fractional Fourier transform.

2. NOTATION AND PRELIMINARIES

Notation. We write $x \cdot y$ for the scalar product on \mathbb{R}^n and $|t|^2 = t \cdot t$, for $t, x, y \in \mathbb{R}^n$. For expressions $A, B \geq 0$, we use the notation $A \leq B$ to represent the inequality $A \leq cB$ for a suitable constant c > 0, and $A \asymp B$ for the equivalence $c^{-1}B \leq A \leq cB$.

The Schwartz class is denoted by $\mathcal{S}(\mathbb{R}^n)$, the space of tempered distributions by $\mathcal{S}'(\mathbb{R}^n)$. We use the brackets $\langle f, g \rangle$ to denote the extension to $\mathcal{S}'(\mathbb{R}^n) \times \mathcal{S}(\mathbb{R}^n)$ of the inner product $\langle f, g \rangle = \int f(t)\overline{g(t)}dt$ on $\mathcal{S}(\mathbb{R}^n)$.

Metaplectic Operators. The metaplectic representation μ of $Mp(n,\mathbb{R})$, the two-sheeted cover of the symplectic group $Sp(n,\mathbb{R})$, defined in (1) arises as intertwining operator between the standard Schrödinger representation ρ of the Heisenberg group \mathbb{H}^d and the representation that is obtained from it by composing ρ with the action of $Sp(n,\mathbb{R})$ by automorphisms on \mathbb{H}^d (see, e.g., [15, 21, 23]). Let us recall the main points of a direct construction.

The symplectic group $Sp(n,\mathbb{R})$ is generated by the so-called free symplectic matrices

$$S = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \in Sp(n, \mathbb{R}), \quad \det B \neq 0.$$

To each such a matrix the associated generating function is defined by

$$W(x, x') = \frac{1}{2}DB^{-1}x \cdot x - B^{-1}x \cdot x' + \frac{1}{2}B^{-1}Ax' \cdot x'.$$

Conversely, to every polynomial of the type

$$W(x,x') = \frac{1}{2}Px \cdot x - Lx \cdot x' + \frac{1}{2}Qx' \cdot x'$$

with

$$P = P^T, Q = Q^T$$

and

$$\det L \neq 0$$

it can be associated a free symplectic matrix, namely

$$S_W = \begin{pmatrix} L^{-1}Q & L^{-1} \\ PL^{-1}Q - L^T & PL^{-1} \end{pmatrix}.$$

Given S_W as above and $m \in \mathbb{Z}$ such that

 $m\pi \equiv \arg \det L \mod 2\pi$,

the related operator $\widehat{S}_{W,m}$ is defined by setting, for $\psi \in \mathcal{S}(\mathbb{R}^n)$,

(14)
$$\widehat{S}_{W,m}\psi(x) = \frac{1}{i^{n/2}}\Delta(W)\int_{\mathbb{R}^n} e^{2\pi i W(x,x')}\psi(x')dx'$$

(with $i^{n/2} = e^{i\pi n/4}$) where

$$\Delta(W) = i^m \sqrt{|\det L|}.$$

The operator $\widehat{S}_{W,m}$ is named quadratic Fourier transform associated to the free symplectic matrix S_W (as a remark, for integral representations of metaplectic operators that do not arise from free symplectic matrices see [14, 24]). The class modulo 4 of the integer m is called *Maslov index* of $\widehat{S}_{W,m}$. Observe that if m is one choice of Maslov index, then m + 2 is another equally good choice: hence to each function W we associate two operators, namely $\widehat{S}_{W,m}$ and $\widehat{S}_{W,m+2} = -\widehat{S}_{W,m}$.

The quadratic Fourier transform corresponding to the choices $S_W = J$ and m = 0 is denoted by \widehat{J} . The generating function of J is simply $W(x, x') = -x \cdot x'$. It follows that

(15)
$$\widehat{J}\psi(x) = \frac{1}{i^{n/2}} \int_{\mathbb{R}^n} e^{-2\pi i x \cdot x'} \psi(x') dx' = \frac{1}{i^{n/2}} \mathcal{F}\psi(x)$$

for $\psi \in \mathcal{S}(\mathbb{R}^n)$, where \mathcal{F} is the usual unitary Fourier transform.

The quadratic Fourier transforms $\widehat{S}_{W,m}$ form a subset of the group $\mathcal{U}(L^2(\mathbb{R}^n))$ of unitary operators acting on $L^2(\mathbb{R}^n)$, which is mapped into itself by the operation of inversion and they generate a subgroup of $\mathcal{U}(L^2(\mathbb{R}^n))$ which is, by definition, the metaplectic group $Mp(n,\mathbb{R})$. The elements of $Mp(n,\mathbb{R})$ are called metaplectic operators.

Hence, every $\widehat{S} \in Mp(n, \mathbb{R})$ is, by definition, a product

$$\widehat{S}_{W_1,m_1}\dots \widehat{S}_{W_k,m_k}$$

of metaplectic operators associated to free symplectic matrices.

Indeed, it can be proved that every $\widehat{S} \in Mp(n, \mathbb{R})$ can be written as a product of exactly two quadratic Fourier transforms: $\widehat{S} = \widehat{S}_{W,m}\widehat{S}_{W',m'}$. Now, it can be shown that the mapping $\widehat{S}_{W,m} \longmapsto S_W$ extends to a group homomorphism $\pi: Mp(n, \mathbb{R}) \to Sp(n, \mathbb{R})$, which is in fact a double covering. We also observe that each metaplectic operator is, by construction, a unitary operator in $L^2(\mathbb{R}^n)$, but also an automorphism of $\mathcal{S}(\mathbb{R}^n)$ and of $\mathcal{S}'(\mathbb{R}^n)$.

We are interested in its restriction $\widehat{S} = \pi(S)$, with $S \in U(2n, \mathbb{R})$, the symplectic rotations in (2).

Observe that $U(n) := U(n, \mathbb{C})$, the complex unitary group (the group of $n \times n$ invertible complex matrices V satisfying $VV^* = V^*V = I_n$) is isomorphic to $U(2n, \mathbb{R})$. The isomorphism ι is the mapping $\iota : U(n) \to U(2n, \mathbb{R})$ given by

(16)
$$\iota(A+iB) = \begin{pmatrix} A & -B \\ B & A \end{pmatrix},$$

for details see [15, Chapter 2.3].

We present here some results related to the group $U(2n, \mathbb{R})$, which will be used in the sequel to attain the characterization of Theorem 1.2. First, we recall a well-known result, see for instance [22, Lemma 9.4.3]:

Lemma 2.1. For $f, g \in L^2(\mathbb{R}^n)$ and $S \in Sp(n, \mathbb{R})$, the STFT $V_q f$ satisfies

(17)
$$|V_{\widehat{S}g}(\widehat{S}f)(x,\xi)| = |V_gf(S^{-1}(x,\xi))|, \quad (x,\xi) \in \mathbb{R}^{2n}.$$

This second issue is contained in [5], we sketch the proof for the sake of consistency.

Lemma 2.2. For $\varphi, \psi \in \mathcal{S}(\mathbb{R}^n)$ and $S \in U(2n, \mathbb{R})$, the STFT $V_{\varphi}(\widehat{S}\psi)$ is a Schwartz function, with seminorms uniformly bounded when $S \in U(2n, \mathbb{R})$.

Proof. Since $\varphi \in \mathcal{S}(\mathbb{R}^n)$, the STFT V_{φ} is a continuous mapping from $\mathcal{S}(\mathbb{R}^n)$ into $\mathcal{S}(\mathbb{R}^{2n})$ (see [16]). Hence, it is enough to show that

$$\{\hat{S}\varphi: S \in U(2n,\mathbb{R})\}$$

is a bounded subset of the Schwartz class $\mathcal{S}(\mathbb{R}^n)$, i.e., every Schwartz seminorm is bounded on it. Since the group $U(2n, \mathbb{R})$ is compact, it is sufficient to show that every seminorm is locally bounded, that is, we can limit ourselves to consider Sin a sufficiently small neighbourhood for any fixed $S_0 \in U(2n, \mathbb{R})$. Equivalently, we can consider S of the form $S = S_1 J^{-1} S_0$ where S_1 belongs to a enough small neighbourhood of J in $U(2n, \mathbb{R})$. Using the representation of metaplectic operators recalled at the beginning of this section, we can write

$$\hat{S}\varphi(x) = \pm \widehat{S}_1[\widehat{J}^{-1}\widehat{S}_0\varphi](x)$$
$$= c\sqrt{|\det L|} \int_{\mathbb{R}^n} e^{2\pi i (\frac{1}{2}Px \cdot x - Lx \cdot y + \frac{1}{2}Qy \cdot y)} [\underbrace{\widehat{J}^{-1}\widehat{S}_0\varphi}_{\in\mathcal{S}(\mathbb{R}^n)}](y)dy$$

where |c| = 1 and, we might say, $||P|| < \epsilon$, $||Q|| < \epsilon$, $||L - I|| < \epsilon$. If $\epsilon < 1$, it is straightforward to check that $\hat{S}\varphi$ belongs to a bounded subset of $\mathcal{S}(\mathbb{R}^n)$, as desired.

Lemma 2.3. Let $B = (b_{i,j})_{i,j=1,...n}$ be the $n \times n$ submatrix in (2). The subset $\Sigma \subset U(2n, \mathbb{R})$ obtained by setting $b_{i,1} = 0$, i = 1, ..., n (i.e., the first column of B is set to zero), is a submanifold of codimension n.

Proof. We have to verify that the coordinates $b_{1,1}, \ldots, b_{n,1}$ are independent on the subset Σ , namely the projection

$$(b_{1,1},\ldots,b_{n,1}):U(2n,\mathbb{R})\to\mathbb{R}^n$$

has rank n on Σ .

Let us first show that for every $S_0 \in \Sigma$ there exists a $U(2n, \mathbb{R})$ -valued smooth function $S(b_1, \ldots, b_n)$, defined in a neighbourhood of $0 \in \mathbb{R}^n$, such that $S(0) = S_0$ and the first column "of its submatrix B" is precisely $(b_1, \ldots, b_n)^T$.

Let $S_0 = A + iB = (V_1, \ldots, V_n) \in \Sigma$, with V_j being a $n \times 1$ complex vector, $j = 1, \ldots, n$, so that by assumption $(b_{i,1})_{i=1,\ldots,n} = \text{Im } V_1 = 0$. We consider any smooth function $V_1(b_1, \ldots, b_n)$, defined in a neighbourhood of $0 \in \mathbb{R}^n$, valued in the unit sphere of \mathbb{C}^n , such that

Im
$$V_1(b_1, \ldots, b_n) = (b_1, \ldots, b_n)^T$$
, $V_1(0) = V_1$.

Then, we apply the Gram-Schmidt orthonormalization procedure in \mathbb{C}^n to the set of vectors $(V_1(b_1,\ldots,b_n), V_2,\ldots,V_n)$. This provides the desired U(n)-valued function $S(b_1,\ldots,b_n)$. In particular $S(0) = S_0$.

Now, the composition of the mapping

$$(b_1,\ldots,b_n)\mapsto S(b_1,\ldots,b_n)$$

followed by the projection $(b_{1,1}, \ldots, b_{n,1}) : U(2n, \mathbb{R}) \to \mathbb{R}^n$ is therefore the identity mapping in a neighbourhood of 0 and has rank n. Hence the same is true for the projection $(b_{1,1}, \ldots, b_{n,1}) : U(2n, \mathbb{R}) \to \mathbb{R}^n$ at S_0 .

Lemma 2.4. For every $\epsilon > 0$, define the (x-independent) function

(18)
$$\chi_{\epsilon}(x,\xi) = \frac{1}{\epsilon^n} \mathbb{1}_Q\left(\frac{\xi}{\epsilon}\right),$$

where

$$Q = \left[-\frac{1}{2}, \frac{1}{2}\right]^n \subset \mathbb{R}^n \quad and \quad \mathbb{1}_Q = \begin{cases} 1, \ \xi \in Q\\ 0, \ \xi \notin Q \end{cases}$$

and

(19)
$$\tilde{\chi}_{\epsilon}(z) = \frac{\chi_{\epsilon}(z)}{\int_{U(2n,\mathbb{R})} \chi_{\epsilon}(Sz) \, dS}, \quad z \in \mathbb{R}^{2n}.$$

Then we have

(20)
$$\int_{U(2n,\mathbb{R})} \tilde{\chi}_{\epsilon}(Sz) \, dS = 1, \quad \forall z \in \mathbb{R}^{2n}$$

and

(21)
$$\lim_{\epsilon \to 0^+} \int_{\mathbb{R}^{2n}} \tilde{\chi}_{\epsilon}(x,\xi) \Phi(x,\xi) dx d\xi = C \int_{\mathbb{R}^n} |x|^n \Phi(x,0) dx$$

for some C > 0 and for every continuous function Φ on \mathbb{R}^{2n} with a rapid decay at infinity.

Proof. We will show in a moment that, for $z = (x, \xi) \in \mathbb{R}^{2n}$,

(22)
$$\int_{U(2n,\mathbb{R})} \chi_{\epsilon}(Sz) \, dS \gtrsim \min\{\epsilon^{-n}, |z|^{-n}\}$$

(with the convention, at z = 0, that $\min\{\epsilon^{-n}, +\infty\} = \epsilon^{-n}$). In particular, $\int_{U(2n,\mathbb{R})} \chi_{\epsilon}(Sz) dS \neq 0$, for every $z \in \mathbb{R}^{2n}$. Formula (20) then follows, because

$$\int_{U(2n,\mathbb{R})} \tilde{\chi}_{\epsilon}(Sz) \, dS = \int_{U(2n,\mathbb{R})} \frac{\chi_{\epsilon}(Sz)}{\int_{U(2n,\mathbb{R})} \chi_{\epsilon}(USz) \, dU} dS$$
$$= \int_{U(2n,\mathbb{R})} \frac{\chi_{\epsilon}(Sz)}{\int_{U(2n,\mathbb{R})} \chi_{\epsilon}(Uz) \, dU} dS = 1$$

for every $z \in \mathbb{R}^{2n}$, since the Haar measure is right invariant.

Let us now prove (22). For z = 0 we have

$$\int_{U(2n,\mathbb{R})} \chi_{\epsilon}(Sz) \, dS = \frac{1}{\epsilon^n} \int_{U(2n,\mathbb{R})} dS = \frac{C_0}{\epsilon^n}$$

with $C_0 = meas(U(2n, \mathbb{R})) > 0$. Consider now $z \neq 0$. Observe that the function

$$\Psi_{\epsilon}(z) := \int_{U(2n,\mathbb{R})} \chi_{\epsilon}(Sz) \, dS$$

is constant on the orbits of $U(2n, \mathbb{R})$ in \mathbb{R}^{2n} , so that we can suppose

$$z = (x, 0), \quad x = (x_1, 0, \dots, 0), \quad x_1 = |x| = |z| > 0$$

Now, by the definition of χ_{ϵ} and Ψ_{ϵ} , (23)

$$\Psi_{\epsilon}(z) = \epsilon^{-n} \operatorname{meas} \left\{ S = \begin{pmatrix} A & -B \\ B & A \end{pmatrix} \in U(2n, \mathbb{R}) : |b_{i,1}| < \frac{\epsilon}{2|z|}, \ i = 1, \dots, n \right\},$$

where $(b_{i,1})_{i=1,\dots,n}$, is the first column of the matrix $B = (b_{i,j})_{i,j=1,\dots,n}$. Define, for $\mu > 0$,

$$f(\mu) = meas \left\{ S = \begin{pmatrix} A & -B \\ B & A \end{pmatrix} \in U(2n, \mathbb{R}) : |b_{i,1}| < \mu, \ i = 1, \dots, n \right\}.$$

Observe that $f(\mu)$ is non-decreasing and constant for $\mu \geq 1$. Moreover, from Lemma 2.3 we know that by setting $b_{i,1} = 0$, $i = 1, \ldots, n$, in $U(2n, \mathbb{R})$, we get a submanifold Σ of codimension n, and the function $f(\mu)$ is the measure of a tubular neighbourhood of Σ in $U(2n, \mathbb{R})$. Hence we have the asymptotic behaviour

(24)
$$\mu^{-n} f(\mu) \to C_0 > 0, \text{ as } \mu \to 0^+$$

and in particular

(25)
$$f(\mu) \gtrsim \min\{1, \mu^n\}.$$

We then infer

(26)
$$\Psi_{\epsilon}(z) = \epsilon^{-n} f\left(\frac{\epsilon}{2|z|}\right) \to \frac{C_1}{|z|^n}, \quad \text{as } \epsilon \to 0^+$$

locally uniformly in $\mathbb{R}^{2n} \setminus \{0\}$, with $C_1 = 2^{-n}C_0$, and

(27)
$$\Psi_{\epsilon}(z) \gtrsim \epsilon^{-n} \min\left\{1, \left(\frac{\epsilon}{|z|}\right)^{n}\right\} = \min\{\epsilon^{-n}, |z|^{-n}\},$$

which is (22).

Let us finally prove (21). We are interested in the limit $\epsilon \to 0^+$, so we can assume $\epsilon \leq 1$. Consider a continuous function Φ on \mathbb{R}^{2n} with rapid decay at infinity. By definition of $\tilde{\chi}_{\epsilon}(z)$ in (19) we have

$$\tilde{\chi}_{\epsilon}(x,\xi) = \frac{\epsilon^{-n}}{\Psi_{\epsilon}(x,\xi)} \mathbb{1}_{[-\epsilon/2,\epsilon/2]^n}(\xi)$$

so that, by (27),

$$|\tilde{\chi}_{\epsilon}(x,\xi)\Phi(x,\xi)| \lesssim \epsilon^{-n}(1+|x|^n)\mathbb{1}_{[-\epsilon/2,\epsilon/2]^n}(\xi)|\Phi(x,\xi)| \in L^1(\mathbb{R}^{2n})$$

for $0 < \epsilon \leq 1$. Fubini's Theorem then allows one to look at the first integral in (21) as an iterated integral

$$I_{\epsilon} := \int_{\mathbb{R}^n} \left(\int_{\mathbb{R}^n} \tilde{\chi}_{\epsilon}(x,\xi) \Phi(x,\xi) d\xi \right) dx$$

and we apply the dominated convergence theorem to the integral with respect to the x variable as follows. Setting

$$\Upsilon_{\epsilon}(x) := \int_{\mathbb{R}^n} \tilde{\chi}_{\epsilon}(x,\xi) \Phi(x,\xi) d\xi = \epsilon^{-n} \int_{[-\epsilon/2,\epsilon/2]^n} \frac{1}{\Psi_{\epsilon}(x,\xi)} \Phi(x,\xi) d\xi,$$

by (26) we have, for every fixed $x \neq 0$,

$$\Upsilon_{\epsilon}(x) \to C|x|^n \Phi(x,0);$$

for some constant C > 0. On the other hand $\Upsilon_{\epsilon}(x)$ is dominated, using (27), by

$$(1+|x|)^n \sup_{\xi \in \mathbb{R}^n} |\Phi(x,\xi)| \in L^1(\mathbb{R}^n).$$

Hence

$$\lim_{\epsilon \to 0^+} I_{\epsilon} = \int_{\mathbb{R}^n} \lim_{\epsilon \to 0^+} \Upsilon_{\epsilon}(x) dx = C \int_{\mathbb{R}^n} |x|^n \Phi(x,0) \, dx.$$

This concludes the proof.

Remark 2.5. Observe that there are no conditions on the derivatives of the function Φ in (21).

3. PROOFS OF THE MAIN RESULTS

In what follows we prove Theorems 1.2 and 1.3.

Proof of Theorem 1.2. (i) **First Step.** Let us start with showing that formula (5) is true for any function ψ in the Schwartz class $\mathcal{S}(\mathbb{R}^n) \subset M^p(\mathbb{R}^n)$, $1 \leq p < \infty$. Using the Gaussian $\varphi(t) = 2^{d/4} e^{-\pi |t|^2}$ as window function, we compute the M_m^p -norm of ψ as in (4) and then use Lemma 2.4 so that

$$\begin{split} \|\psi\|_{M^p_m}^p &= \int_{\mathbb{R}^{2n}} |V_{\varphi}\psi(z)|^p m(z)^p \, dz = \int_{\mathbb{R}^{2n}} \int_{U(2n,\mathbb{R})} \tilde{\chi}_{\epsilon}(Sz) |V_{\varphi}\psi(z)|^p m(z)^p \, dSdz \\ &= \int_{\mathbb{R}^{2n}} \int_{U(2n,\mathbb{R})} \tilde{\chi}_{\epsilon}(z) |V_{\varphi}\psi(S^{-1}z)|^p m(S^{-1}z)^p \, dSdz \\ &= \int_{\mathbb{R}^{2n}} \int_{U(2n,\mathbb{R})} \tilde{\chi}_{\epsilon}(z) |V_{\widehat{S}\varphi} \widehat{S}\psi(z)|^p m(S^{-1}z)^p \, dSdz \end{split}$$

where in the last equality we used Lemma 2.1. Observe that, since S is unitary and φ is a Gaussian, $\hat{S}\varphi = c\varphi$, for some phase factor $c \in \mathbb{C}$, with |c| = 1 (see [15, Proposition 252]) and this phase factor is killed by the modulus obtaining $|V_{\hat{S}\varphi}\hat{S}\psi(z)| = |V_{\varphi}\hat{S}\psi(z)|$. Continuing the above computation we infer

$$\left\|\psi\right\|_{M^p_m}^p = \int_{\mathbb{R}^{2n}} \tilde{\chi}_{\epsilon}(z) \int_{U(2n,\mathbb{R})} |V_{\varphi}\widehat{S}\psi(z)|^p m(S^{-1}z)^p \, dSdz$$

 Set

$$\Phi(z) = \int_{U(2n,\mathbb{R})} |V_{\varphi}\widehat{S}\psi(z)|^p m(S^{-1}z)^p \, dS$$

The dominated convergence theorem guarantees that Φ is continuous on \mathbb{R}^{2n} and moreover Φ has rapid decay at infinity. This follows from Lemma 2.2 (recall that *m* is continuous and has at most polynomial growth).

Letting $\epsilon \to 0^+$ and using (21) we obtain

$$\begin{aligned} \|\psi\|_{M_m^p}^p &= C \int_{\mathbb{R}^n} |x|^n \int_{U(2n,\mathbb{R})} |V_{\varphi} \widehat{S} \psi(x,0)|^p m(S^{-1}(x,0)^T)^p \, dS \, dx \\ &= C \int_{\mathbb{R}^n} |x|^n \int_{U(2n,\mathbb{R})} |\langle \widehat{S} \psi, T_x \varphi \rangle|^p m(S^{-1}(x,0)^T)^p \, dS \, dx \\ &= C \int_{\mathbb{R}^n} |x|^n \int_{U(2n,\mathbb{R})} |\langle \psi, \widehat{S} T_x \varphi \rangle|^p m(S(x,0)^T)^p \, dS \, dx. \end{aligned}$$

The last equality is due to $\langle \widehat{S}\psi, T_x\varphi \rangle = \langle \psi, \widehat{S}^{-1}T_x\varphi \rangle$ and the invariance of the Haar measure of $U(2n, \mathbb{R})$ with respect to the change of variable $S \to S^{-1}$.

Second Step. Consider $f \in M_m^p(\mathbb{R}^n)$, $1 \leq p < \infty$. Using the density of the Schwartz class $\mathcal{S}(\mathbb{R}^n)$ in $M_m^p(\mathbb{R}^n)$ (cf. e.g., [22, Chapter 12]), there exists a sequence $\{\psi_k\}_k \in \mathcal{S}(\mathbb{R}^n)$ such that $\psi_k \to f$ in $M_m^p(\mathbb{R}^n)$. This implies that $\psi_k \to f$ in $\mathcal{S}'(\mathbb{R}^n)$ and

$$\langle \psi_k, \widehat{S}T_x\varphi \rangle \to \langle \psi, \widehat{S}T_x\varphi \rangle$$

pointwise for every $x \in \mathbb{R}^n$, $S \in U(2n, \mathbb{R})$. Let us define, for every $f \in M^p_m(\mathbb{R}^n)$,

(28)
$$|||f||| = \left(\int_{\mathbb{R}^n \times U(2n,\mathbb{R})} |x|^n |\langle f, \widehat{S}T_x\varphi\rangle|^p m(S(x,0)^T)^p dxdS \right)^{\frac{1}{p}}.$$

By Fatou's Lemma, for any $f \in M_m^p(\mathbb{R}^n)$:

(29)
$$|||f|||^{p} \leq \liminf_{k \to \infty} |||\psi_{k}|||^{p} \lesssim \liminf_{k \to \infty} ||\psi_{k}||_{M_{m}^{p}}^{p} = ||f||_{M_{m}^{p}}^{p}.$$

It is easy to check that |||f||| is a seminorm on $M_m^p(\mathbb{R}^n)$. Applying (29) to the difference $f - \psi_k$ we obtain $|||f - \psi_k||| \to 0$ and hence $|||\psi_k||| \to |||f|||$. By assumption we also have $\|\psi_k\|_{M_m^p} \to \|f\|_{M_m^p}$, and the desired norm equivalence in (5) then extents from $\mathcal{S}(\mathbb{R}^n)$ to $M_m^p(\mathbb{R}^n)$.

Third Step. We will show that (6) easily follows from (5). By the definition of the symplectic group (1), for any $S \in U(2n, \mathbb{R})$,

$$J^{-1}S = (S^T)^{-1}J^{-1} = SJ^{-1}$$

for $S^{-1} = S^T$. On the other hand, for any $f \in M^p_m(\mathbb{R}^n)$, $||f||_{M^p_m} \asymp ||\hat{f}||_{M^p_{\tilde{m}}}$, with $\tilde{m}(z) = m(J^{-1}z)$; see [16]. Using (15),

$$\begin{aligned} |\langle \hat{f}, \widehat{S}T_x\varphi\rangle| &= |\langle f, \widehat{J^{-1}}\widehat{S}T_x\varphi\rangle| = |\langle f, \widehat{S}\mathcal{F}^{-1}T_x\varphi\rangle| \\ &= |\langle f, \widehat{S}M_x\mathcal{F}^{-1}\varphi\rangle| = |\langle f, \widehat{S}M_x\varphi\rangle| \end{aligned}$$

since the Gaussian is an eigenvector of \mathcal{F}^{-1} with eigenvalue equal to 1. Moreover

$$\tilde{m}(S(x,0)^T) = m(J^{-1}S(x,0)^T) = m(SJ^{-1}(x,0)^T) = m(S(0,x)^T).$$

Hence (6) follows from (5).

(ii) Case $p = \infty$. Observe that any $z \in \mathbb{R}^{2n}$ can be written as

$$z = S^{-1}(x, 0)^T,$$

for some $x \in \mathbb{R}^n$, $S \in U(2n, \mathbb{R})$, so that, for any $f \in M_m^{\infty}(\mathbb{R}^n)$,

$$\begin{split} \|f\|_{M_m^{\infty}(\mathbb{R}^n)} &= \sup_{z \in \mathbb{R}^{2n}} |V_{\varphi}f(z)| m(z) \asymp \sup_{S \in U(2n,\mathbb{R})} \sup_{x \in \mathbb{R}^n} |V_{\varphi}f(S^{-1}(x,0)^T)| m(S^{-1}(x,0)^T) \\ &= \sup_{S \in U(2n,\mathbb{R})} \sup_{x \in \mathbb{R}^n} |V_{\varphi}(\widehat{S}f)(x,0)| m(S^{-1}(x,0)^T) \\ &= \sup_{S \in U(2n,\mathbb{R})} \sup_{x \in \mathbb{R}^n} |\langle \widehat{S}f, T_x \varphi \rangle| m(S^{-1}(x,0)^T) \\ &= \sup_{S \in U(2n,\mathbb{R})} \sup_{x \in \mathbb{R}^n} |\langle f, \widehat{S}T_x \varphi \rangle| m(S(x,0)^T), \end{split}$$

which gives (7). Formula (8) follows as above.

We now prove the similar result, with the group $U(2n, \mathbb{R})$ replaced by the subgroup \mathbb{T}^n (up to isomorphisms).

Proof of Theorem 1.3. (i) We could follow a similar pattern to the proof of Theorem 1.2, replacing the group $U(2n, \mathbb{R})$ by \mathbb{T}^n . The preparation of Lemma 2.3 would be no longer necessary. Lemma 2.4 would require some small adjustments. On the other hand a more direct argument can be given. Namely, writing $z_j = (x_j, \xi_j)$ in complex notation as $r_j e^{i\theta_j}$, and setting $r = (r_1, \ldots, r_n)$, $\theta = (\theta_1, \ldots, \theta_n)$ we have

$$\|f\|_{M^p_m}^p = \int_{\mathbb{R}^{2n}} |V_{\varphi}f(z)|^p m(z)^p \, dz$$

= $\int_{\mathbb{R}^n_+ \times [0,2\pi]^n} r_1 \cdots r_n |V_{\varphi}f(r_1 e^{i\theta_1}, \dots, r_n e^{i\theta_n})|^p m(r_1 e^{i\theta_1}, \dots, r_n e^{i\theta_n})^p \, dr \, d\theta.$

With S as in (9) and using Lemma 2.1, therefore we have

$$\begin{split} \|f\|_{M^p_m}^p &\asymp \int_{\mathbb{R}^n \times \mathbb{T}^n} |x_1 \cdots x_n| |V_{\varphi} f(S(x,0)^T)|^p m(S(x,0)^T)^p \, dx \, dS \\ &= \int_{\mathbb{R}^n \times \mathbb{T}^n} |x_1 \cdots x_n| |V_{\varphi} (\widehat{S}^{-1} f)(x,0)|^p m(S(x,0)^T)^p \, dx \, dS \\ &= \int_{\mathbb{R}^n \times \mathbb{T}^n} |x_1 \cdots x_n| |\langle \widehat{S}^{-1} f, T_x \varphi \rangle|^p m(S(x,0)^T)^p \, dx \, dS, \end{split}$$

which is (10). The characterization (11) has the same proof as the corresponding formula (6).

(ii) The M^{∞} case uses the same argument as in the proofs of (7) and (8), with the group $U(2n, \mathbb{R})$ replaced by \mathbb{T}^n .

4. Integral representations for the torus in terms of the fractional Fourier transform

Observe that the symplectic matrix in $U(2n, \mathbb{R})$ corresponding to the complex matrix $S \in \mathbb{T}^n$ in (9) via the isomorphism ι in (16) is given by

$$\iota(S) = \begin{pmatrix} A & -B \\ B & A \end{pmatrix}$$

with

 $A = \operatorname{diag} [\cos \theta_1, \dots, \cos \theta_n]$ $B = \operatorname{diag} [\sin \theta_1, \dots, \sin \theta_n].$ Consider the case $\theta_i \neq k\pi, k \in \mathbb{Z}, i = 1, \dots, n$. The matrix $\iota(S)$ is a free symplectic matrix and the related metaplectic operator possesses the integral representation (14). Since

$$AB^{-1} = B^{-1}A = \operatorname{diag}\left[\frac{\cos\theta_1}{\sin\theta_1}, \dots, \frac{\cos\theta_n}{\sin\theta_n}\right],$$

the polynomial W(x, x') becomes

(30)
$$W(x_1, \dots, x_n, x'_1, \dots, x'_n) = \sum_{i=1}^n \frac{1}{2\sin\theta_i} (\cos\theta_i x_i^2 - 2x_i x'_i + \cos\theta_i x'^2_i)$$

and

$$\Delta(W) = \frac{c}{\sqrt{|\sin\theta_1 \cdots \sin\theta_n|}}$$

for some phase factor $c \in \mathbb{C}$, with |c| = 1. Hence we obtain, for $\psi \in \mathcal{S}(\mathbb{R}^n)$,

(31)
$$\widehat{\iota(S)}\psi(x) = \frac{c}{\sqrt{|\sin\theta_1 \cdots \sin\theta_n|}} \int_{\mathbb{R}^n} e^{2\pi i W(x,x')} \psi(x') dx',$$

with W(x, x') in (30). From (31) we deduce that $\widehat{\iota(S)}$ can be written as the composition of the operators

(32)
$$\widehat{\iota(S)} = \pm \widehat{\iota(S_1)} \cdots \widehat{\iota(S_n)},$$

where, for some phase factor c,

$$\widehat{\iota(S_i)}\psi(x) = \frac{c}{\sqrt{|\sin\theta_i|}} \int_{\mathbb{R}} e^{\frac{\pi i}{\sin\theta_i}(\cos\theta_i x_i^2 - 2x_i x_i' + \cos\theta_i x_i'^2)} \psi(x_1', \dots, x_i', \dots, x_n') dx_i'.$$

Indeed if $\theta_i = \pi/2$, then $\widehat{\iota(S_i)} = \pm \widehat{J}$ is the Fourier transform with respect to the variable x_i . Otherwise, $\widehat{\iota(S_i)} = \pm \mathcal{F}_{\theta_i}$, the θ_i -angle partial fractional Fourier transform (again referred to the variable x_i).

Alternatively, the same conclusion (32) can be drawn by writing

(33)
$$S = \operatorname{diag} \left[e^{i\theta_1} \dots , e^{i\theta_n} \right] = \operatorname{diag} \left[e^{i\theta_1} , 1, \dots 1 \right] \cdots \operatorname{diag} \left[1, \dots 1, e^{i\theta_n} \right]$$
that is

$$S = S_1 \cdots S_i \cdots S_n,$$

with

$$S_i = \text{diag}[1, \dots, 1, e^{i\theta_i}, 1, \dots, 1], \quad i = 1, \dots, n$$

so that

$$\widehat{\iota(S)} = \iota(S_1) \cdots \iota(S_1) = \pm \widehat{\iota(S_1)} \cdots \widehat{\iota(S_n)}.$$

If $\theta_i = 2k\pi$ for some $k \in \mathbb{Z}$, $\widehat{\iota(S_i)} = \pm I$ with I the identity operator. If $\theta_i = (2k+1)\pi$ for some $k \in \mathbb{Z}$, $\widehat{\iota(S_i)}\psi(x) = \pm \psi(x_1, \dots, -x_i, \dots, x_n)$.

Hence using the θ_i -angle partial fractional Fourier transform $\mathcal{F}_{\theta_i} = \pm \widehat{\iota(S_i)}$ we can rephrase Theorem 1.3 as follows.

Theorem 4.1. Let φ be the Gaussian of Theorem 1.2. (i) For $1 \leq p < \infty$, $f \in M^p_m(\mathbb{R}^n)$, we have

$$\|f\|_{M^p_m(\mathbb{R}^n)} \asymp \left(\int_{\mathbb{R}^n \times [0,2\pi]^n} |x_1 \dots x_n| |\langle f, \mathcal{F}_{\theta_1} \dots \mathcal{F}_{\theta_n} T_x \varphi \rangle |^p m(x_1 e^{i\theta_1}, \dots, x_n e^{i\theta_n})^p dx d\theta \right)^{\frac{1}{p}},$$

and

$$\|f\|_{M^p_m(\mathbb{R}^n)} \asymp \left(\int_{\mathbb{R}^n \times [0,2\pi]^n} |\xi_1 \dots \xi_n| |\langle f, \mathcal{F}_{\theta_1} \dots \mathcal{F}_{\theta_n} M_\xi \varphi \rangle |^p m(\xi_1 e^{i\theta_1}, \dots, \xi_n e^{i\theta_n})^p d\xi d\theta \right)^{\frac{1}{p}}.$$

(*ii*) For $p = \infty$,

$$||f||_{M_m^{\infty}(\mathbb{R}^n)} \asymp \sup_{\theta \in [0,2\pi]^n} \sup_{x \in \mathbb{R}^n} |\langle f, \mathcal{F}_{\theta_1} \dots \mathcal{F}_{\theta_n} T_x \varphi \rangle |m(x_1 e^{i\theta_1}, \dots, x_n e^{i\theta_n})|$$

and

$$\|f\|_{M_m^{\infty}(\mathbb{R}^n)} \asymp \sup_{\theta \in [0,2\pi]^n} \sup_{\xi \in \mathbb{R}^n} |\langle f, \mathcal{F}_{\theta_1} \dots \mathcal{F}_{\theta_n} M_{\xi} \varphi \rangle |m(\xi_1 e^{i\theta_1}, \dots, \xi_n e^{i\theta_n}).$$

We observe that this result could also be obtained by writing $||f||_{M_m^p(\mathbb{R}^n)}$ in terms of the weighted L^p norm of the Bargmann transform of f and using the covariance property of the Bargmann transform; the papers [18, 30] and specially [31] are relevant in this connection.

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