Evaluating Jacquet's GL($\mathbf{n}$) Whittaker function

Version: 4th November 2005

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Algorithms for the explicit symbolic and numeric evaluation of Jacquet's Whittaker function for the $GL(n,\mathbb{R})$ based generalized upper half plane for $n \geq 2$ and an implementation for symbolic evaluation in the Mathematica package GL(n)pack are described. This required a careful study of the different definition of Whittaker function which appear in the literature.

Key Words: K-Bessel function, Whittaker function, Jacquet Whittaker function, symbolic evaluation, quadrature, unbounded domain

MSC2000: 33C15, 22E30, 11E57, 11E76.

1. INTRODUCTION

2. DEFINITIONS

Use [4] as the standard for definitions and point out where we have found ones that differ in the literature.
$GL(n)$ means $GL(n,\mathbb{R})$. Always, unless otherwise noted, $n \geq 2$.
From [4, Definition 2.4.1], let $b_{i,j} := ij$ when $i + j \leq n$ and $(n-i)(n-j)$ otherwise, and $\nu = (\nu_1, \cdots, \nu_{n-1}) \in \mathbb{C}^{n-1}$, then the so-called **power function** $I_\nu : \mathfrak{h}^n \to \mathbb{C}$ is defined by:

$$I_\nu(z) := \prod_{i=1}^{n-1} \prod_{j=1}^{n-1} y_i^{b_{i,j}\nu_j}, \tag{1}$$

where $z \equiv x.y$ is the **Iwasawa form**, i.e. $z = x.y.o.d$, where o is orthogonal, d is non-zero and in the center and

$$x.y = \begin{pmatrix} 1 & x_{1,2} & x_{1,3} & & x_{1,n} \\ & 1 & x_{2,3} & & x_{2,n} \\ & & \ddots & & \vdots \\ & & & 1 & x_{n-1,n} \\ & & & & 1 \end{pmatrix} . \begin{pmatrix} y_1 y_2 \cdots y_{n-1} & & & & \\ & y_1 y_2 \cdots y_{n-2} & & & \\ & & \ddots & & \\ & & & y_1 & \\ & & & & 1 \end{pmatrix} .$$

and both x and y are unique. Examples of the power function in dimensions 2,3,4:

$$\begin{aligned} I_\nu(y_1) &= y_1^{\nu_1}, \\ I_\nu(y_1,y_2) &= y_1^{\nu_1+2\nu_2} y_2^{2\nu_1+\nu_2}, \\ I_\nu(y_1,y_2,y_3) &= y_1^{\nu_1+2\nu_2+3\nu_3} y_2^{2\nu_1+4\nu_2+2\nu_3} y_3^{3\nu_1+2\nu_2+\nu_3}. \end{aligned}$$

Note that Friedberg [3] and Stade [11] reverse the order of the y_i's in the Iwasawa form.

Definition 2.1. Let $S = U_n(\mathbb{R})$ be the subgroup of upper triangular unipotent matrices. A function $\psi : S \to \mathbb{C}$ which can be written in the form

$$\psi(u) = \prod_{i=1}^{n-1} e^{2\pi i m_{n-i+1} u_{i,i+1}},$$

for some $n-1$ tuple of integers $m = (m_1, \cdots, m_{n-1})$, is called a **character** or character of $U_n(\mathbb{R})$. We write ψ_m for ψ, and in case each $m_i = 1$ write ψ_1. Note that $\psi(a.b) = \psi(a)\psi(b)$ for $a, b \in U_n(\mathbb{R})$ and that all characters of $U_n(\mathbb{R})$ have this form. Note also that [4] begins with a direct order for the m_i and then reverses the order for the definition of the Jacquet Whittaker function as given here.

From [4, Definition 5.9.2], if $n \geq 2$ and $\nu = (\nu_1, \cdots, \nu_{n-1})$:

$$\begin{aligned} \Gamma_\nu &:= \prod_{j=1}^{n-1} \prod_{j \leq k \leq n-1} \pi^{-\frac{1}{2} - v_{j,k}} \Gamma(\tfrac{1}{2} + v_{j,k}) \text{ where} \\ v_{j,k} &:= \sum_{i=0}^{j-1} \frac{n\nu_{n-k+i} - 1}{2}. \end{aligned}$$

Definition 2.2. [4, Proposition 2.3.1] The associative algebra D^n is the algebra of operators generated by real linear combinations of the operators $D_{\alpha_1} \circ \cdots \circ D_{\alpha_k}$ where each α_i is an $n \times n$ real matrix, D_α is defined for smooth functions F acting on elements $g \in GL(n, \mathbb{R})$ by

$$D_\alpha F(g) := \frac{\partial}{\partial t} F(g + tg.\alpha))|_{t=0},$$

and $D_\alpha \circ D_\beta$ is the composition of operators. The center of this algebra is denoted $\mathfrak{D}^n$.

Definition 2.3. [4, Definition 1.3.1] Let $a, b \geq 0$. The **Siegel set** $\Sigma_{a,b} \subset \mathfrak{h}^n$ is the set of all $z = x.y \in \mathfrak{h}^n$ with $|x_{i,j}| \leq b$ for $1 \leq i < j \leq n$ and $y_i > a$ for $1 \leq i \leq n-1$.

From [4, Definition 5.4.1], for $n \geq 2$ and $\nu = (\nu_1, \cdots, \nu_{n-1})$ and ψ a character of $U_n(\mathbb{R})$, a smooth function $W : \mathfrak{h}^n \to \mathbb{C}$ is called an $SL(n, \mathbb{Z})$-Whittaker function of type ν (or for short a **Whittaker function**) if it satisfies the following conditions:

(1) $W(uz) = \psi(u)W(z)$ for all $u \in U_n(\mathbb{R}), z \in \mathfrak{h}^n$,
(2) $DW(z) = \lambda_D W(z)$ for all $D \in \mathfrak{D}^n$, $z \in \mathfrak{h}^n$,
(3) $\int_\Omega |W(z)|^2 d^*z < \infty$ where Ω is $\Sigma_{\frac{\sqrt{3}}{2}, \frac{1}{2}}$ and d^*z is the left invariant quotient measure.

Definition 2.4. The matrix $w_n \in SL(n,\mathbb{Z})$ has a 0 in each row and column except for the reverse leading diagonal entries which are either $(-1)^{[n/2]}$ in the $(1,n)^{\text{th}}$ position or 1 in every other position. That is to say:

$$w_n = \begin{pmatrix} & & & (-1)^{[n/2]} \\ & & 1 & \\ & \cdot & & \\ & \cdot & & \\ 1 & & & \end{pmatrix}$$

Compare the so-called "long-element" permutation matrix w, which is the same as w_n except the $(1,n)^{\text{th}}$ element has the value 1.

Definition 2.5. The left invariant **quotient measure** on $\mathfrak{h}^n$ [4, Proposition 1.5.3] :

$$\begin{aligned} d^*z &= d^*x \cdot d^*y \quad \text{where} \\ d^*x &= \prod_{1\le i<j\le n} dx_{i,j} \quad \text{and} \\ d^*y &= \prod_{k=1}^{n-1} y_k^{-k(n-k)-1} dy_k. \end{aligned}$$

The definition of Jacquet's Whittaker function as given in [4, Eqn 5.5.1] and called "Jacquet's integral" is given by:

$$W_J(z;\nu,\psi_m) := \int_{U_n(\mathbb{R})} I_\nu(w_n \cdot u \cdot z)\overline{\psi_m(u)} d^*u,$$

where $z \in \mathfrak{h}^n$, $\nu \in \mathbb{C}^{n-1}$, ψ_m is a character with $m = (m_{n-1},\cdots,m_1) \in \mathbb{Z}^{n-1}$ and with no $m_i = 0$ and where the measure is inherited from that on $\mathfrak{h}^n$. The main properties of this function are summarized in:

Theorem 2.1. *[4, Proposition 5.5.2]] Let $n \ge 2$. Assume $\Re(\nu_i) > 1/n$ for $1 \le i \le n-1$ and that non-zero integers m_i with $1 \le i \le n-1$ are given. Then Jacquet's integral converges absolutely and uniformly on compact subsets of $\mathfrak{h}^n$ and has meromorphic continuation to all $\nu \in \mathbb{C}^{n-1}$. The function $W_J(z;\nu,\psi_m)$ is an $SL(n,\mathbb{Z})$-Whittaker function of type ν and character ψ_m and satisfies the identity*

$$W_J(z;\nu,\psi_m) = c_{\nu,m} \cdot \psi_m(x) \cdot W_J(My;\nu,\psi_1),$$

where $c_{\nu,m} \ne 0$ depends only on m and ν, and where the diagonal matrix M has i^{th} entry

$$|m_1 m_2 \cdots m_{n-i}|$$

for $1 \le i \le n-1$ and n^{th} entry 1 and where the explict value of the constant $c_{\nu,m}$ is given in Theorem 7.1 below.

Theorem 2.2. *In the definition of Jacquet's Whittaker function the matrix w_n can be replaced by the matrix w.*

Proof. If for $1 \le j \le n$, e_j is the standard unit vector then $e_j.w_n = e_j.w$ for all $j > 1$. The theorem now follows from the exterior product form of the power function given in [4, Lemma 5.7.2]. ∎

3. RELATION TO STADE'S WHITTAKER FUNCTION

The GL(n)pack function `Whittaker` computes a symbolic iterated integral representation of the generalized Jacquet Whittaker function $W_{Jacquet}$ (also written W_J) of order n, for $n \geq 2$, as defined above. The algorithm uses the recursive representation of the Whittaker function derived by Stade [Stade, 1990, Theorem 2.1], but his Whittaker functions are not the same as those of [4]. Let W_S and W_S^* be Stade's Whittaker and Whittaker starred functions respectively and let Γ_ν represent the gamma factors for either form as given in Definition 2.1 above. Make the following additional definitions:

Definition 3.1.

$$\begin{aligned} H_\nu(y) &:= I_\nu(y_{n-1}, \cdots, y_1), \\ Q = Q_\nu(y) &:= H_\nu(y) \prod_{j=1}^{n-1} y_j^{-\mu_j} \quad \text{where,} \\ \mu_j &:= \sum_{k=1}^{n-j} r_{j,k} \quad \text{for } 1 \leq j \leq n-1 \text{ and where,} \\ r_{j,k} &:= (\sum_{i=k}^{k+j-1} \frac{n\nu_i}{2}) - \frac{j}{2} \quad \text{for } 1 \leq j \leq n-1, 1 \leq k \leq n-j. \end{aligned}$$

Definition 3.2.

$$\begin{aligned} W_S(y;\nu,\psi_1) = W_{n,\nu}(y) &:= \Gamma_\nu \int_{U_n(\mathbb{R})} H_\nu(w \cdot u \cdot y)\overline{\psi_1(u)} d^*u, \\ W_S^*(y;\nu,\psi_1) = W_{n,\nu}^*(y) &:= W_S(y;\nu,\psi_1)/Q. \end{aligned}$$

The notations $W_{n,\nu}, W_{n,\nu}^*$ are from [11]. Note that the first differs from his $W_{n,a}$ [12].

Theorem 3.1. *Let $n \geq 2$ and for $y = (y_1, \cdots, y_{n-1})$ let $y_r = (y_{n-1}, \cdots, y_1)$ be the vector with coordinates reversed. Then the relationship between the two definitions of Whittaker function for $\mathfrak{h}^n$ may be expressed by the equalities:*

$$Q_\nu(y_r) * W_S^*(y_r;\nu,\psi_1) = \Gamma_\nu * W_J(y;\nu,\psi_1) = W_J^*(y;\nu,\psi_1) = W_S(y_r;\nu,\psi_1).$$

Stade's recursive formula for the Whittaker function:

Theorem 3.2. *[11, Theorem 2.1] as amended in [12] If $n \geq 3$ and $\nu \in \mathbb{C}^{n-1}$, for $2 \leq j \leq n-2$ let $\lambda = (\lambda_1, \cdots, \lambda_{n-3})$ where $\lambda_{j-1} := n\nu_j/(n-2)$, set $u_0 = 0, 1/u_{n-1} = 0$ and $u_{n-1}^0 = 1$.*

$$\begin{aligned} W_S^*(y;\nu,\psi_1) &= 1 \quad \text{if } n = 0 \text{ or } 1, \\ W_S^*(y;\nu,\psi_1) &= 2K_{\nu-\frac{1}{2}}(2\pi y_1) \quad \text{if } n = 2, \\ W_S^*(y;\nu,\psi_1) &= 8\int_0^\infty u^{\frac{3\nu_1-3\nu_2-2}{2}} K_{\frac{3\nu_1+3\nu_2-2}{2}}(2\pi\sqrt{1+\frac{1}{u_1^2}}y_1) K_{\frac{3\nu_1+3\nu_2-2}{2}}(2\pi\sqrt{1+u_1^2}y_2)du_1 \quad \text{for } n = 3, \\ W_S^*(y;\nu,\psi_1) &= 2^{2n-3}\int_{(\mathbb{R}+)^{n-2}} \{\prod_{i=1}^{n-1} u_i^{r_{i,1}-r_{i,n-i}} K_{\mu_1}(2\pi y_i\sqrt{(1+u_{i-1}^2)(1+1/u_i^2)})\} \\ &\times\ W_S^*((\frac{y_2u_1}{u_2}, \cdots, \frac{y_{n-2}u_{n-3}}{u_{n-2}}), (\lambda_1, \cdots, \lambda_{n-3})) \prod_{i=1}^{n-2} \frac{du_i}{u_i} \end{aligned}$$

for $n \geq 4$, where the quantities $r_{i,j}$ are defined in terms of the ν_i in Definition 3.1 above.

4. CLASSICAL WHITTAKER FUNCTIONS

Properties of classical Whittaker functions are well known. However we record them here to show the relationship between the classical and GL(n)pack functions.
Whittaker's equation [16, 8, 9] for $W_{k,\mu}(z)$ c/- [4, p57] is given by:

$$w'' + (-\frac{1}{4} + \frac{k}{z} + \frac{\frac{1}{4} - \mu^2}{z^2})w = 0$$

where $\mu \in \mathbb{C}$, $k \in \mathbb{R}$ and $z \in \mathbb{C}$.
Solutions for this equation have the integral representation [16, 8, 9]:

$$W_{k,\mu}(z) = \int_0^\infty e^{-t} t^{\mu - k - \frac{1}{2}} (1 + \frac{t}{z})^{\mu - k - \frac{1}{2}} dt$$

for $\Re\mu - k - \frac{1}{2} > 0$.
Solutions also have a series representation [16, 8, 9]: Let $\Psi(\alpha, \gamma; z)$ be the so-called **confluent hypergeometric function of the second kind** satisfying

$$\Psi(\alpha, \gamma; z) = z^{-\alpha}\Big(\sum_{k=0}^{n} \frac{(-1)^k (\alpha)_k (1 + \alpha - \gamma)_k}{k!} z^{-k} + O(\frac{1}{|z|^{n+1}}\Big),$$

for $|\arg z| < \pi - \delta$ for all fixed $\delta > 0$. Then we can write

$$W_{k,\mu}(z) = z^{\mu + \frac{1}{2}} e^{-\frac{z}{2}} \Psi(\tfrac{1}{2} - k + \mu, 2\mu + 1; z).$$

5. EVALUATION OF THE COMPLEX ORDER FUNCTION $K_\nu(X)$.

The expressions for Whittaker functions are given in terms of the modified Bessel function of the second order $K_\nu(z)$, rather than $W_{k,\nu}(z)$. This is traditional rather than essential, but should be useful, given the way K-Bessel functions appear in many other number-theory oriented computations.
Define for $\Re z > 0$, and $\nu \in \mathbb{C}$ [4, p57] or [15]:

$$K_\nu(z) = \frac{1}{2} \int_0^\infty e^{-\frac{z}{2}(t + \frac{1}{t})} t^{\nu - 1} dt$$

Or for $|\arg z| < \pi$, [8, p204]:

$$K_\nu(z) = \sqrt{\pi}(2z)^\nu e^{-z} \Psi(\nu + \tfrac{1}{2}, 2\nu + 1; 2z).$$

Asymptotic values for $\Re\nu > 0$ [9, p454] as $z \to \infty$ with $|\arg z| \leq 3\pi/2 - \delta$:

$$K_\nu(z) \sim \sqrt{\frac{\pi}{2z}} e^{-z}$$

Asymptotic values for $\Re\nu > 0$ [9, p454] as $z \to 0$ with $|\arg z| \leq B$:

$$K_\nu(z) \sim \frac{\Gamma(\nu)}{2} (\frac{z}{2})^{-\nu}$$

Integral relations [9, p254]. For $\Re\mu > |\Re\nu|$:

$$\int_0^\infty t^{\mu-1}K_\nu(t)dt = 2^{\mu-2}\Gamma(\frac{\mu+\nu}{2})\Gamma(\frac{\mu-\nu}{2}),$$

and for $\Re\,\nu > -\frac{1}{2}$, $|\arg z| < \frac{\pi}{2}$:

$$K_\nu(z) = \frac{\sqrt{\pi}(\frac{1}{2}z)^\nu}{\Gamma(\nu+\frac{1}{2})}\int_1^\infty e^{-zt}(t^2-1)^{\nu-\frac{1}{2}}dt.$$

By [5, §3.384, 9.6], If $\Re\nu > \frac{1}{2}$ and $p \neq 0$:

$$\int_{-\infty}^\infty \frac{e^{-ipx}}{(x^2+1)^\nu}dx = \frac{2\pi}{2^\nu}\frac{|p|^\nu}{\Gamma(\nu)}W_{0,\frac{1}{2}-\nu}(2|p|).$$

The system Mathematica™ gives for $\Re\nu > \frac{1}{2}$ and $y \neq 0$:

$$\int_{-\infty}^\infty \frac{e^{-2\pi iyx}}{(x^2+1)^\nu}dx = \frac{2\pi^\nu|y|^{\nu-\frac{1}{2}}}{\Gamma(\nu)}K_{\nu-\frac{1}{2}}(2\pi|y|),$$

where the property $K_s(z) = K_{-s}(z)$ has been used.
It follows from the series representations for the K-Bessel and classical Whittaker functions that for all ν and $|\arg z| < \pi - \delta$,

$$\sqrt{\frac{2z}{\pi}}K_\nu(z) = W_{0,\nu}(2z).$$

Comparing this with Stade's W_S in dimension n=2 the reason for the term "Whittaker" finally comes clear.

6. UNIFORMIZATION OF THE DEFINITIONS OF WHITTAKER FUNCTION IN DIMENSIONS 2 AND 3

Dimension 2: We have [4, Eqn. 5.5.4]:

$$\begin{aligned} W_J(z;\nu,\psi_m) &= \frac{2|m|^{\nu-\frac{1}{2}}\pi^\nu}{\Gamma(\nu)}\sqrt{y}K_{\nu-\frac{1}{2}}(2\pi|m|y)\cdot e^{2\pi imx} \\ \Gamma_\nu &= |m\pi|^{-\nu}\Gamma(\nu). \end{aligned}$$

Stade's form for dimension 2 [11] is:

$$W_S(y;\nu,\psi_1) = 2\sqrt{y}K_{\nu-\frac{1}{2}}(2\pi y).$$

THEOREM 6.1. *Let $n=2$ so $z = x+iy$. Assume for $y>0$ and $\Re\nu > \frac{1}{2}$ that*

$$W_S(y,\nu,\psi_1) = 2\sqrt{y}K_{\nu-\frac{1}{2}}(2\pi y) \text{ and } W_J(z,\nu,\psi_m) = y^{1-\nu}\int_{-\infty}^\infty \frac{e^{-2\pi imuy}}{(1+u^2)^\nu}du\cdot e^{2\pi imx}.$$

Then

$$W_J(z,\nu,\psi_m) = |m|^{\nu-1}\cdot(\frac{\pi^\nu}{\Gamma(\nu)})\cdot 2\sqrt{y}K_{\nu-\frac{1}{2}}(2\pi|m|y)\cdot e^{2\pi imx}.$$

Proof. This follows from the assumptions using the Mathematica expression for the infinite integral given above and the relationship $W_J = \frac{\pi^\nu}{\Gamma(\nu)} W_S$. ∎

Note that the only difference between this form and that of [4, Eqn. 5.5.4] is the constant $c_{\nu,m} = |m|^{\nu-1}$, a form consistent with Theorem 7.1 below.

Dimension 3: By [4, Eqn 6.1.3] and [11, Page 318] (Note that like Friedberg, Stade swops the order of the labels on the y_i but Goldfeld makes the swop back, but no other changes. This is Stade's form:

$$\begin{aligned} W_S((y_1,y_2);(\nu_1,\nu_2),\psi_{1,1}) &= 8y_1^{1-\frac{\nu_1-\nu_2}{2}} y_2^{1+\frac{\nu_1-\nu_2}{2}} \int_0^\infty K_{\frac{3\nu_1+3\nu_2-2}{2}}(2\pi y_1\sqrt{1+u^{-2}}) \\ &\times\ K_{\frac{3\nu_1+3\nu_2-2}{2}}(2\pi y_2\sqrt{1+u^2}) u^{\frac{3\nu_1-3\nu_2}{2}} \frac{du}{u} \\ \Gamma_\nu &= \pi^{\frac{1}{2}} - 3\nu_1 - 3\nu_2 \Gamma(\frac{3\nu_1}{2})\Gamma(\frac{3\nu_2}{2})\Gamma(\frac{3\nu_1+3\nu_2-1}{2}). \end{aligned}$$

GL(n)pack has the same gamma factor. The coefficient 4 (as given by [4, 11] but since corrected [12] is given its corrected value 8.

7. EVALUATION OF THE CONSTANT

THEOREM 7.1. *The constant in Theorem 2.1 has value*

$$c_{\nu,m} = \prod_{i=1}^{n-1} |m_i|^{\sum_{j=1}^{n-1} b_{i,j}\nu_j - i(n-i)}.$$

Proof. 1. As in [4, Prop. 5.5.2] let

$$M = \begin{pmatrix} |m_1 m_2 \cdots m_{n-1}| & & & & \\ & |m_1 m_2 \cdots m_{n-2}| & & & \\ & & \ddots & & \\ & & & |m_1| & \\ & & & & 1 \end{pmatrix}.$$

Let $d_n = 1$ and for $1 \le i \le n-1$, $d_i = |m_1| \cdots |m_{n-i}|$ so $u.M = M.\hat{u}$ where for $1 \le i < j \le n-1$:

$$u_{i,j} = \hat{u}_{i,j} \frac{d_i}{d_j} = \hat{u}_{i,j} |m_{n-j+1}| \cdots |m_{n-i}|.$$

If we let $u_i = u_{n-i,n-i+1}$ for $1 \le i \le n-1$, and similarly define $\hat{u}_i$, then under the transformation $u \to \hat{u}$ we have

$$u_i = \hat{u}_i |m_i|, 1 \le i \le n-1.$$

The (absolute value of the determinant of the) Jacobian of the transformation $u \to \hat{u}$ is

$$J(\frac{u}{\hat{u}}) = \prod_{i<j} |m_{n-j+1}| \cdots |m_{n-i}| = \prod_{i=1}^{n-1} |m_i|^{i(n-i)}.$$

2. It follows that

$$\begin{aligned} W_J(Mz;\nu,\psi_{\epsilon_1,\cdots,\epsilon_{n-1}}) &= \int_{U_n(\mathbb{R})} I_\nu(w.u.Mz)e^{-2\pi i(\epsilon_1 u_1+\cdots+\epsilon_{n-1}u_{n-1})}d^*u \\ &= J(\frac{u}{\hat{u}})\int_{U_n(\mathbb{R})} I_\nu(w.M\hat{u}.z)e^{-2\pi i(|m_1|\epsilon_1\hat{u}_1+\cdots+|m_{n-1}|\epsilon_{n-1}\hat{u}_{n-1})}d^*\hat{u} \\ &= J(\frac{u}{\hat{u}})\int_{U_n(\mathbb{R})} I_\nu(w.M.w.w.\hat{u}.z)e^{-2\pi i(m_1\hat{u}_1+\cdots+m_{n-1}\hat{u}_{n-1})}d^*\hat{u} \\ &= \prod_{i=1}^{n-1}\prod_{j=1}^{n-1}|m_i|^{-b_{i,j}\nu_j}J(\frac{u}{\hat{u}})\int_{U_n(\mathbb{R})} I_\nu(\omega_n.\hat{u}.z)e^{-2\pi i(m_1\hat{u}_1+\cdots+m_{n-1}\hat{u}_{n-1})}d^*\hat{u} \\ &= \gamma_{m,\nu}\cdot W_J(z;\nu,\psi_m) \quad (1) \end{aligned}$$

where we have used $w.M.w$ is a diagonal matrix with elements in the reverse order from those of M and where

$$\gamma_{\nu,m} = \frac{\prod_{i=1}^{n-1}|m_i|^{i(n-i)}}{\prod_{i=1}^{n-1}\prod_{j=1}^{n-1}|m_i|^{b_{i,j}\nu_j}}.$$

3. Next, by taking the Iwasawa form for $z = x.y$, commuting M and x ($M.x = \hat{x}.M$), and then making the transformation $\hat{u} = u.\hat{x}$ (which has Jacobian 1), we obtain the form

$$W_J(Mz;\nu,\psi_{\epsilon_1,\cdots,\epsilon_{n-1}}) = \psi_m(x)\cdot W_J(My;\nu,\psi_{\epsilon_1,\cdots,\epsilon_{n-1}}) \quad (2)$$

4. Now consider the $n-j^{th}$ row of the matrix u with $1\le j\le n-1$:

$$(0,\cdots,0,1,u_j,u_{n-j,n-j+2},\cdots,u_{n-j,n}).$$

If δ_j is the diagonal matrix with 1's in every position except the $n-j^{th}$ which is ϵ_j, and we make the transformation $\hat{u} = \delta_j.u$ with Jacobian determinant ϵ_j^j, then, since $w.\delta_j = \delta_{n-j+1}.w$ and $I_\nu(\delta_{n-j+1}.z) = I_\nu(z)$, (because δ_{n-j+1} is orthogonal and diagonal matrices commute), we can write:

$$\begin{aligned} W_J(My;\nu,\psi_{\epsilon_1,\cdots,\epsilon_{n-1}}) &= \int_{U_n(\mathbb{R})} I_\nu(w.\delta_j.\delta_j.u.My)e^{-2\pi i(\epsilon_1 u_1+\cdots+\epsilon_{n-1}u_{n-1})}d^*u \\ &= |\epsilon_j^j|\int_{U_n(\mathbb{R})} I_\nu(\delta_{n-j+1}.w.\hat{u}.My)e^{-2\pi i(\epsilon_1\hat{u}_1+\cdots+\hat{u}_j+\cdots+\epsilon_{n-1}\hat{u}_{n-1})}d^*\hat{u} \\ &= W_J(My;\nu,\psi_{\epsilon_1,\cdots,1,\cdots,\epsilon_{n-1}}) \end{aligned}$$

where the subscript 1 is in the j^{th} position.

One may do the above procedure for each j with $1\le j\le n-1$ to obtain:

$$W_J(My;\nu,\psi_{\epsilon_1,\cdots,\epsilon_{n-1}}) = W_J(My;\nu,\psi_{1,\cdots,1}) \quad (3).$$

Finally, combining the expressions (1), (2) and (3) we derive the equation

$$W_J(z;\nu,\psi_m) = c_{\nu,m}\cdot\psi_m(x)\cdot W_J(My;\nu,\psi_{1,\cdots,1})$$

where

$$\begin{aligned} c_{\nu,m} &= \gamma_{\nu,m}^{-1} \\ &= \prod_{i=1}^{n-1}|m_i|^{\sum_{j=1}^{n-1}b_{i,j}\nu_j - i(n-i)}. \end{aligned}$$

▮

Here is a listing of the first $n = 2$ thru $n = 5$ $c_{m,\nu}$ values:

$$
\begin{aligned}
c_{2,\nu} &= |m_1|^{\nu_1-1}, \\
c_{3,\nu} &= |m_1|^{\nu_1+2\nu_2-2}|m_2|^{2\nu_1+\nu_2-2}, \\
c_{4,\nu} &= |m_1|^{\mathrm{v}_1+2\,\mathrm{v}_2+3\,\mathrm{v}_3-3}\,|m_2|^{2\,v_1+4\,v_2+2\,v_3-4}\,|m_3|^{3\,v_1+2\,v_2+\mathrm{v}_3-3}, \\
c_{5,\nu} &= |m_1|^{\mathrm{v}_1+2\,\mathrm{v}_2+3\,\mathrm{v}_3+4\,\mathrm{v}_4-4}\,|m_2|^{2\,v_1+4\,v_2+6\,v_3+3\,v_4-6} \\
&\times\ |m_3|^{3\,v_1+6\,v_2+4\,v_3+2\,v_4-6}\,|m_4|^{4\,v_1+3\,v_2+2\,v_3+\mathrm{v}_1-4}.
\end{aligned}
$$

8. COMPUTATION OF $W_J(Z, \nu, \psi)$ AND VALIDATION

Computation of the Whittaker function was divided into symbolic evaluation and numeric evaluation. The former is more straight forward than the latter and was able to be included in GL(n)pack . The numerical code uses the symbolic form as an initial step. Stade's form W_S^* was computed using his recursive reformulation Theorem 3.1, which was converted first to a single multiple integral and then, by a change of variables using the inverse hyperbolic tangent in each variable, to an integral over a cube of appropriate dimension. This has a number of decided advantages over any direct use of Jacquet's integral for numerical computation: firstly the oscillation implied by the character ψ_1 is removed, and secondly the exponential decay of the K-Bessel functions at infinity assists the speed and accuracy of any quadrature application.
Stade's form was then converted into the function W_J using Theorem 3.1.
Examples of the GL(n)pack output are given below, in Figure 1 dimensions 2, 3,in Figure 2 dimension 4 and in Figure 3 dimension 5 [2]:

```
In[114]:=
        Whittaker[{{y1, 0}, {0, 1}}, {v1}, {1}, u][[4]]
```

Out[114]=

$$\frac{2\,\pi^{\mathrm{v1}}\sqrt{\mathrm{y1}}\;\mathrm{K}[-\frac{1}{2}+\mathrm{v1},\,2\,\pi\,\mathrm{y1}]}{\mathrm{Gamma}[\mathrm{v1}]}$$

```
In[115]:=
        Whittaker[{{y1 y2, 0, 0}, {0, y1, 0}, {0, 0, 1}}, {v1, v2}, {1, 1}, u][[4]]
```

Out[115]=

$$\left(8\,\pi^{-\frac{1}{2}+3\,\mathrm{v1}+3\,\mathrm{v2}}\,\mathrm{y1}^{1+\frac{\mathrm{v1}}{2}-\frac{\mathrm{v2}}{2}}\,\mathrm{y2}^{1-\frac{\mathrm{v1}}{2}+\frac{\mathrm{v2}}{2}}\int_0^\infty \mathrm{u}^{-1+\frac{3\,(\mathrm{v1}-\mathrm{v2})}{2}}\,\mathrm{K}\Big[\frac{1}{2}\,(-2+3\,\mathrm{v1}+3\,\mathrm{v2}),\,2\,\pi\sqrt{1+\mathrm{u}^2}\,\mathrm{y1}\Big]\right.$$

$$\left.\mathrm{K}\Big[\frac{1}{2}\,(-2+3\,\mathrm{v1}+3\,\mathrm{v2}),\,2\,\pi\sqrt{1+\frac{1}{\mathrm{u}^2}}\,\mathrm{y2}\Big]\,d\mathrm{u}\right)\Big/$$

$$\left(\mathrm{Gamma}\Big[\frac{3\,\mathrm{v1}}{2}\Big]\,\mathrm{Gamma}\Big[\frac{3\,\mathrm{v2}}{2}\Big]\,\mathrm{Gamma}\Big[\frac{1}{2}\,(-1+3\,\mathrm{v1}+3\,\mathrm{v2})\Big]\right)$$

FIG. 1. The GL(n)pack Whittaker functions in dimensions 2 and 3.

To validate the numerical computations (and thus the symbolic forms computed by GL(n)pack), and give some idea of their accuracy, we used a result highlighted in [12, p126], namely that if the power function is defined using some especially chosen new parameters, then the Whittaker functions are invariant under all permutations of those parameters. These permutations give rise to functional equations, which on the face of it differ from those set out in [4, Theorem 5.9.8]. These permutations were used here in a simpler manner: a permutation of an explicit set of values for the new parameters

```
In[116]:=
        Whittaker[{{y1 y2 y3, 0, 0, 0}, {0, y1 y2, 0, 0}, {0, 0, y1, 0}, {0, 0, 0, 1}},
          {v1, v2, v3}, {1, 1, 1}, u][[4]]

Out[116]=
```

$$\left(64\,\pi^{-2+6\,v1+8\,v2+6\,v3}\,y1^{\frac{3}{2}+v1-v3}\,y2^{2}\,y3^{\frac{3}{2}-v1+v3}\int_0^{\infty}\int_0^{\infty}K\left[-\frac{1}{2}+2\,v2,\ \frac{2\,\pi\,y2\,u[1]}{u[2]}\right]K\left[-\frac{3}{2}+2\,v1+2\,v2+2\,v3,\ 2\,\pi\,y3\sqrt{1+\frac{1}{u[1]^2}}\right]K\left[-\frac{3}{2}+2\,v1+2\,v2+2\,v3,\ 2\,\pi\,y2\sqrt{(1+u[1]^2)\left(1+\frac{1}{u[2]^2}\right)}\right]K\left[-\frac{3}{2}+2\,v1+2\,v2+2\,v3,\ 2\,\pi\,y1\sqrt{1+u[2]^2}\right](u[1]\,u[2])^{-1+2\,v1-2\,v3}\,du[2]\,du[1]\right)\Big/$$

$$\left(\mathrm{Gamma}[2\,v1]\,\mathrm{Gamma}[2\,v2]\,\mathrm{Gamma}\left[-\frac{1}{2}+2\,v1+2\,v2\right]\mathrm{Gamma}[2\,v3]\,\mathrm{Gamma}\left[-\frac{1}{2}+2\,v2+2\,v3\right]\mathrm{Gamma}[-1+2\,v1+2\,v2+2\,v3]\right)$$

FIG. 2. The GL(n)pack Whittaker functions in dimension 4.

a_i give rise to two corresponding sets of values in the original parameters ν_i. These corresponding sets should be in or close to the domain of absolute convergence of the Whittaker function $\Re\nu_i > 1/n$ to give convergence of the integral forms.
In more detail, set

$$H_{n,a}(y) := \prod_{j=1}^{n-1} y_j \prod_{j=1}^{n-1} y_j^{a_j}$$

where the (a_j) are $n-1$ complex numbers. Then set $a_n = -a_1 - \cdots - a_n$. When defined using this power function the Whittaker function is invariant under all permutations of the (a_i). Then define ν in terms of a by setting $I_\nu(y) = H_{n,a}(y_r)$ and note that the first product term in the definition of H is invariant under reversal of the order of the y_i. These relations in dimensions 3 through 5 are as follows:

$$\begin{aligned}
\text{Dimension } 3: \nu_1 &= (1+a_1+2a_2)/3\\
\nu_2 &= (1+a_1-a_2)/3\\
\text{Dimension } 4: \nu_1 &= (1+a_1+a_2+2a_3)/4\\
\nu_2 &= (1+a_2-a_3)/4\\
\nu_3 &= (1+a_1-a_2)/4\\
\text{Dimension } 5: \nu_1 &= (1+a_1+a_2+a_3+2a_4)/5\\
\nu_2 &= (1+a_3-a_4)/5\\
\nu_3 &= (1+a_2-a_3)/5\\
\nu_4 &= (1+a_1-a_2)/5
\end{aligned}$$

In this study, the Mathematica general adaptive quadrature routine `NIntegrate` was used, with the option Method set of `MultiDimensional` and the precision set to `MachinePrecision`. The processor was an Intel Pentium 4. No improvement was found using the function Compile. This is no doubt because most of the work is done by `NIntegrate`, which is already compiled. The values given are for the

```
In[1]:= Whittaker[{{y1 y2 y3 y4, 0, 0, 0, 0}, {0, y1 y2 y3, 0, 0, 0}, {0, 0, y1 y2, 0, 0},
         {0, 0, 0, y1, 0}, {0, 0, 0, 0, 1}}, {v1, v2, v3, v4}, {1, 1, 1, 1}, u][[4]]
```

Out[1]=

$$\Bigg(1024\,\pi^{5\,(-1+2\,v1+3\,v2+3\,v3+2\,v4)}\; y1^{2+\frac{3\,v1}{2}+\frac{v2}{2}-\frac{v3}{2}-\frac{3\,v4}{2}}\, y2^{3+\frac{v1}{2}+v2-v3-\frac{v4}{2}}\, y3^{3-\frac{v1}{2}-v2+v3+\frac{v4}{2}}\, y4^{2-\frac{3\,v1}{2}-\frac{v2}{2}+\frac{v3}{2}+\frac{3\,v4}{2}}$$

$$\int_0^\infty\int_0^\infty\int_0^\infty\left(\int_0^\infty K\left[\frac{1}{2}\,(-2+5\,v2+5\,v3),\ \frac{2\,\pi\,y3\,\sqrt{1+\frac{1}{u[1]^2}}\;u[2]}{u[3]}\right] K\left[\frac{1}{2}\,(-2+5\,v2+5\,v3),\ \frac{2\,\pi\,y2\,\sqrt{1+u[1]^2}\;u[3]}{u[4]}\right] u[1]^{-1+\frac{5\,v2}{2}-\frac{5\,v3}{2}}\,du[1]\right)$$

$$K\left[\frac{1}{2}\,(-4+5\,v1+5\,v2+5\,v3+5\,v4),\ 2\,\pi\,y4\,\sqrt{1+\frac{1}{u[2]^2}}\right]$$

$$K\left[\frac{1}{2}\,(-4+5\,v1+5\,v2+5\,v3+5\,v4),\ 2\,\pi\,y3\,\sqrt{(1+u[2]^2)\left(1+\frac{1}{u[3]^2}\right)}\right]$$

$$K\left[\frac{1}{2}\,(-4+5\,v1+5\,v2+5\,v3+5\,v4),\ 2\,\pi\,y2\,\sqrt{(1+u[3]^2)\left(1+\frac{1}{u[4]^2}\right)}\right]$$

$$K\left[\frac{1}{2}\,(-4+5\,v1+5\,v2+5\,v3+5\,v4),\ 2\,\pi\,y1\,\sqrt{1+u[4]^2}\right]$$

$$u[3]^{\frac{1}{2}\,(-2+5\,v1+5\,v2-5\,v3-5\,v4)}\,(u[2]\,u[4])^{\frac{1}{2}\,(-2+5\,v1-5\,v4)}\,du[2]\,du[3]\,du[4]\Bigg)\Bigg/$$

$$\Bigg(\mathrm{Gamma}\left[\frac{5\,v1}{2}\right]\mathrm{Gamma}\left[\frac{5\,v2}{2}\right]\mathrm{Gamma}\left[\frac{1}{2}\,(-1+5\,v1+5\,v2)\right]$$

$$\mathrm{Gamma}\left[\frac{5\,v3}{2}\right]$$

$$\mathrm{Gamma}\left[\frac{1}{2}\,(-1+5\,v2+5\,v3)\right]$$

$$\mathrm{Gamma}\left[\frac{1}{2}\,(-2+5\,v1+5\,v2+5\,v3)\right]$$

$$\mathrm{Gamma}\left[\frac{5\,v4}{2}\right]$$

$$\mathrm{Gamma}\left[\frac{1}{2}\,(-1+5\,v3+5\,v4)\right]$$

$$\mathrm{Gamma}\left[\frac{1}{2}\,(-2+5\,v2+5\,v3+5\,v4)\right]$$

$$\mathrm{Gamma}\left[\frac{1}{2}\,(-3+5\,v1+5\,v2+5\,v3+5\,v4)\right]\Bigg)$$

FIG. 3. The GL(n)pack Whittaker function in dimension 5.

Whittaker function W_S^*. The timing is from the Mathematica Timingfunction. The results were as follows:

Dimension	v	y	value	timing
3	$\{5/4, 1/4\}$	$\{1, 1\}$	$2.255480212 \times 10^{-8}$	
3	$\{7/6, 5/12\}$	$\{1, 1\}$	$2.255480211 \times 10^{-8}$	0.562s
4	$\{199/520, 23/80, 67/620\}$	$\{1, 1, 1\}$	1.0910×10^{-15}	
4	$\{437/1040, 67/260, 213/1040\}$	$\{1, 1, 1\}$	1.0915×10^{-15}	25703.7s
5	$\{3433/6630, 47/221, 89/510, 3/10\}$	$\{1, 1, 1, 1\}$	5.1976×10^{-28}	
5	$\{558/1105, 3/10, 22/195, 47/221\}$	$\{1, 1, 1, 1\}$	5.1972×10^{-28}	759.8s

Given Theorem 2.1, the uniform nature of the periodicity of the integrand should make the application of modern lattice rule techniques [10] practical for direct numerical evaluation of Jacquet's integral. However given the unbounded domain and slow convergence of the integrand this will require considerable adaptation and analysis.

9. ACKNOWLEDGEMENTS

The assistance of Eric Stade, Dorian Goldfeld, Ross Barnett and Stephen Joe in the development of this material is gratefully acknowledged.

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