On standard $L$-function for generic cusp forms on $U(2,1)$ (Automorphic Forms and Automorphic L-Functions)

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On standard $L$-function for generic cusp forms on $U(2,1)$

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Introduction
The main object of our concern is ramified factors of zeta integrals. By definition, zeta integrals "interpolates" automorphic $L$-functions to deduce their some analytic properties, say meromorphic continuation. But this is just the first step of study of $L$-functions. Actually special values, entireness or poles of $L$-functions encode very deep and fascinating arithmetic information. It is quite hard to investigate these properties. However it has been believed since the beginning of the history of automorphic representations, that through the study of zeta integrals one can reach the depth of arithmetic nature. Besides Jacquet-Langlands theory of the standard $L$-function for $GL(2)$, we should cite a great work [Rama] of Ramakrishnan, which says that the Garrett integral coincides the triple $L$-function including the ramified factors with the help of Ikeda’s archimedean calculus [Ike]. Takloo-Bighash investigate the Novodvorsky integral to determine local factors of the spinor $L$-function for the generic representations of $GSp(4)$ [Tak].

In this note we would like to treat the Gelbart Piatetski-Shapiro integral, which are recalled in §1, and report some results on ramified factors of the standard $L$-function for $U(3)$. In §2, we calculate the "GCD" of $p$-adic components of the zeta integral for the generic representations of $U(3)$. In §3, we redo the calculation of [K-O] to give a cleaner form of the "GCD" of archimedean component.

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1 Gelbart Piatetski-Shapiro zeta integral
Note that we can obtain the same result without any loss of generality, even if we formulate the problem over an arbitrary totally real algebraic number field. So we take $\mathbb{Q}$ for our ground field.
<Group structure>

Let $E$ be an imaginary quadratic extension of $\mathbb{Q}$ and denote the non-trivial element of its Galois group by $\overline{\tau}$. Put

$$G := \{g \in GL(3,E) \mid {}^t \overline{g} \begin{pmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{pmatrix} g = \begin{pmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{pmatrix} \}.$$ 

This defines a quasi-split unitary group of three variables over $\mathbb{Q}$. Let

$$G = NTK$$

be the Iwasawa decomposition of $G$. Then each subgroups are expressed as

$$N = \{ \begin{pmatrix} 1 & b & z \\ 1 & -\overline{b} & 1 \end{pmatrix} \in G \mid b, z \in E, \; z + \overline{z} = -|b|_E^2 \},$$

$$T = \{ \begin{pmatrix} \alpha & \beta \\ \overline{\alpha}^{-1} & \end{pmatrix} \in G \mid \alpha \in E^\times, \beta \in E^{(1)} \}$$

and

$$K = G \cap M_3(\mathcal{O}_E).$$

A Borel subgroup of $G$ is given by

$$B = N \triangleleft T.$$ 

We need a subgroup

$$H := \text{Img}\left( \iota : U(1,1) \ni \begin{pmatrix} * & * \\ * & * \end{pmatrix} \mapsto \begin{pmatrix} * & * \\ 1 & * \\ * & * \end{pmatrix} \in G \right)$$

as the Euler subgroup for a Rankin-Selberg integral. The Iwasawa decomposition of $H$ is

$$H = Z_NAK_H$$

with

$$Z_N = \{ \begin{pmatrix} 1 & z \\ 1 & 1 \end{pmatrix} \in G \mid z \in \mathbb{R} \},$$

$$A = \{ \begin{pmatrix} a \\ 1 \\ a^{-1} \end{pmatrix} \in G \mid a \in \mathbb{Q}^\times \}$$

and

$$K_H = K \cap H.$$
The standard $L$-function>
For a cuspidal automorphic representation $\pi = \otimes_v \pi_v$ of $G(\mathbb{A}) = U(3)_\mathbb{A}$ and a Hecke character $\xi$ of $E$, the standard $L$-function is defined by a local way as an Euler product

$$L(s; \pi \otimes \xi) := \prod_v L_v(s; \pi_v \otimes \xi_v).$$

For the unramified principal series $\pi_p \cong \text{Ind}_{B_p}^{G_p}(\chi)$, the unramified factor is given by

$$L_p(s; \pi_p \otimes \xi_p) := L_{E,p}(s; \xi_p) L_p(2s; \xi_p \chi) L_p(2s; \xi_p/\chi).$$

Zeta integral>
For a generic cusp form $\varphi$ belonging to a generic $\pi$, Gelbart and Piatetski-Shapiro introduced the following zeta integral

$$\mathcal{Z}(s; \varphi, \xi) := \int_{H(\mathbb{Q}) \backslash H(\mathbb{A})} \varphi|_B(h) E^\xi,H(s; h) \mathrm{d}h.$$

Here $E^\xi,H$ is an Eisenstein series on $H(\mathbb{A})$ corresponding to the principal series $\text{Ind}_{(B \cap H)_{\mathbb{A}}}^{H_{\mathbb{A}}}(\xi)$. By the Langlands theory of Eisenstein series the integral is continued to the whole $s$-plane.

Unfolding and local integrals>
Assume the generic cusp form is localizable; $\varphi = \otimes_v \varphi_v$. By using the multiplicity one result on Whittaker models and an unfolding procedure, the Rankin-Selberg integral decomposes into a product of local integrals:

$$\mathcal{Z}(s; \varphi, \xi) = \prod_v \mathcal{Z}_v(s; W, \Phi_\xi^{(s)}),$$

with

$$\mathcal{Z}_v(s; W, \Phi_\xi^{(s)}) := \int_{Z_{N,v} \backslash H_v} W_{\varphi_v}|_{H_v}(h_v) \Phi_\xi^{(s)}(h_v) \mathrm{d}h_v.$$

Here $Z_{N,v}$ is the center of the maximal nilpotent subgroup $N_v$ of $G_v$, $W_{\varphi_v}$ is a Whittaker vector corresponding to $\varphi_v \in \pi_v$ and $\Phi_\xi^{(s)}$ is a special section of the principal series $\text{Ind}_{(B \cap H)_v}^{H_v}(\xi|_{\cdot}^{(s)})$ of $H$ induced up from its Borel subgroup $\iota((\begin{array}{ll}* & * \\ * & * \end{array}))$. Note that this integral vanishes unless $\varphi$ is a generic cusp form.

Over the places where everything is unramified, Gelbart and Piatetski-Shapiro showed the coincidence of local factors of $L$-function and zeta integral by using the Casselman-Shalika formula.

Proposition 1 ([Ge-PS] §4) For the unramified (i.e. $K_p$-spherical) $\pi_p$'s,

$$\mathcal{Z}_p(s; W, \Phi_\xi^{(s)}) = L_p(s; \pi_p \otimes \xi_p).$$

Next step of investigation is to analyze ramified factors. The $p$-adic case was treated by Baruch in his thesis [Ba]. We record two of his results.
Proposition 2 ([Ba]) For any non-archimedean $\pi_p$'s, the followings hold.

i) The family of zeta integrals for the Jacquet sections

$$\{ \mathcal{Z}_p(s; W, \Phi_{\xi, \phi}^{(s)} | K_p - \text{finite } W \in Wh_{\psi}(\pi_p), \phi \in S(Q^2_p) \}$$

admits the "GCD". Note the $\Phi_{\xi, \phi}^{(s)}$'s is dense in the representation space of principal series.

ii) There is a rational function $\tau_p(s; \pi_p, \xi_p; \psi_Q, \chi_E)$ in $q^{-s}$ such that the local functional equation

$$\mathcal{Z}_p(1-s; W, \Phi_{\xi}^{(s)}, \hat{\phi}) = \tau_p(s; \pi_p, \xi_p; \psi_Q, \chi_E) \cdot \mathcal{Z}_p(s; W, \Phi_{\xi, \phi}^{(s)})$$

holds. Here $\hat{\phi}$ is the Fourier transform of $\phi$.

Note that Baruch get the local functional equation by showing the generic multiplicity one for the space of invariant bi-linear forms:

$$\dim_{\mathbb{C}} \text{Bil} \left( \pi_p|_H, \text{Ind}_{(B \cap H)_p}^{H_p}(\xi| \cdot |_E^s) \right) \leq 1$$

for almost all of $s \in \mathbb{C}$. And the explicit form of gamma factor has not been known so far.

The remaining problems are following.

Problems

1) Calculate $\mathcal{Z}_p(s; W, \Phi_{\xi}^{(s)})$ for "bad" finite places $v = p$ to determine the ramified $L$-factor $L_p(s; \pi_p \otimes \xi_p)$ as the "GCD".

2) Calculate archimedean $\mathcal{Z}_\infty(s; W, \Phi_{\xi}^{(s)})$ and study the "GCD".

2 $p$-adic factors

There are several ways to analyze ramified $L$-factors. Here we follow the method of Takloo-Bighash [Tak], where he calculated the Novodvorsky integral for the generic $\pi_p$'s of $GSp(4)$ and determined ramified $L$-factors. The strategy, which is divided into three steps, is simple but relies on Shalika's ingenious fundamental work.

Step 1: Germ expansion of Whittaker functions.

By nature of Whittaker functions, we only need their $A_p$-radial part, which can be expanded as

$$W_{\phi_p}( \begin{pmatrix} a & 1 \\ a^{-1} & a \end{pmatrix} ) = \sum_{c \in S_{\pi_p}} \phi_c(a) \cdot c(a),$$

by using finite functions $c$ on $Q^X_p$. Here coefficient functions $\phi_c$ are Schwartz functions and the index set $S_{\pi_p}$ is a finite set determiner by $\pi_p$. The size of set can be bounded by Shalika's argument on distribution. In our case, $|S_{\pi_p}| \leq 2$.

Step 2: Shahidi theory of intertwiners.

Let $I_{\sigma}(\nu)$ denote the principal series $\text{Ind}_{D_p}^{G_p} \sigma | \cdot |^\nu$ of $G_p$. Here $\sigma$ is given by

$$\sigma: \quad T \rightarrow \mathbb{C}^\times$$

$$\text{diag}(\alpha, \beta, \bar{\alpha}^{-1}) \rightarrow \chi(\alpha)\chi'(\alpha\beta\bar{\alpha}^{-1}),$$
where $\chi$ and $\chi'$ are quasi-character and character of $E^\times_p$ respectively. And $\nu \in \mathbb{C}$ is a complex parameter. Consider the Whittaker vector corresponding to a section $f \in I_\sigma(\nu)$. Then the $A_p$-radial part can be expressed as

$$W_f \left( \begin{array}{cc} a & 1 \\ & a^{-1} \end{array} \right) = \lambda_\sigma(f) \cdot \chi(a) + C(\sigma, w) \left( \lambda_{\sigma^w} A(\nu; \sigma, w) \right)(f) \cdot \chi^{-1}(a).$$

Here $\lambda_\sigma : I_\sigma(\nu) \to \mathbb{C}$ is the Whittaker functional for $I_\sigma(\nu)$ and

$$A(\nu; \sigma, w) : I_\sigma(\nu) \to I_{\sigma^w}(-\nu)$$

is the intertwiner. Similarly $\lambda_{\sigma^w} : I_{\sigma^w}(-\nu) \to \mathbb{C}$ is the Whittaker functional for $I_{\sigma^w}(-\nu)$. The action of Weyl element $w$ is given by $\sigma^w := (\chi^{-1}, \chi')$. The proportional factor $C(\sigma, w)$ is Shahidi’s local coefficients.

Note that if the section $f$ sits in $\pi_p$, then $f$ is our $\varphi_p$. So we need to know which $\pi_p$ is kernel/image of the intertwiner. We appeal to

**Step 3**: Classification result of $\pi_p$’s.

A general result of Shahidi says that the reducing points of the standard modules induced up from maximal parabolic subgroup can be 0, ±1 or ±1/2. In our case, all of these occur.

**Proposition 3 (Ke)** The standard module $I_\sigma(\nu)$ is irreducible except the following three cases.

1) When $\nu = \pm 1$, the constituent of the standard module is given by the exact sequence

$$0 \to St_{\chi'} \to I_\sigma(+1) \to \chi' \cdot \det \to 0.$$

Here $St_{\chi'}$ is the twisted Steinberg representation and is the kernel of $A(+1; \sigma, w)$. For $\nu = -1$, submodule and quotient in the above exact sequence are substituted.

2) When $\nu = \pm 1/2$ and $\chi|\mathbb{Q}_p^\times = \text{sgn}$,

$$0 \to \pi^2 \to I_\sigma(+1/2) \to \pi^{nt} \to 0$$

is an exact sequence. Here $\pi^2$ is a square integrable representation and is the kernel of $A(+1/2; \sigma, w)$. The quotient $\pi^{nt}$ is a non-tempered unitary representation. For $\nu = -1/2$, submodule and quotient are substituted.

3) When $\nu = \pm 0$ and $\chi|\mathbb{Q}_p^\times = 1_{\mathbb{Q}_p^\times}, \chi \neq 1_{\mathbb{F}_p^\times}$, the standard module decomposes into a direct sum

$$I_\sigma(0) = \pi^{\text{deg}} \oplus \pi^{\text{nd}},$$

where $\pi^{\text{deg}}, \pi^{\text{nd}}$ stands for irreducible degenerate, irreducible non-degenerate representations respectively. A general result of Shahidi says that non-degenerate representations can not be annihilated by intertwiners. So the kernel of $A(0; \sigma, w)$ is $\pi^{\text{deg}}$.

Now we define the local factor $L_p(s; \pi_p \otimes \xi_p)$ as the "GCD" of Baruch’s family. Then the above argument gives the following result for special representations and the fact that $Wh_\psi(\pi_p)$ coincides the full $S(Q_p^\times)$ for super-cuspidals.
Theorem 4 The local factor $L_{p}(s; \pi_{p} \otimes \xi_{p})$ of standard $L$-function for $U(3)$ is given as follows.

0) When $\pi_{p}$ is an irreducible standard module $I_{\sigma}(\nu)$,

$$L_{E,p}(s; \xi_{p}) L_{p}(2s + 2\nu; \xi_{p}\chi) L_{p}(2s + 2\nu; \xi_{p}/\chi).$$

1) When $\pi_{p}$ is the twisted Steinberg representation $St_{\chi'}$,

$$L_{E,p}(s; \xi_{p}) L_{p}(2s + 2; \xi_{p}\chi).$$

2) When $\pi_{p}$ is the twisted Steinberg representation $St_{\chi'}$,

$$L_{E,p}(s; \xi_{p}) L_{p}(2s + 1; \xi_{p}\chi).$$

3) When $\pi_{p}$ is the irreducible square-integrable representation $\pi^{2}$,

$$L_{E,p}(s; \xi_{p}) L_{p}(2s; \xi_{p}\chi).$$

4) When $\pi_{p}$ is a super-cuspidal representation,

$$L_{E,p}(s; \xi_{p}).$$

We note that Watanabe studied related subject in a broader setting [Wat], where the representations are limited to regular and tamely ramified though, and covers much of Theorem 4. For the twisted Steinberg representation $St_{\chi'}$, the author calculated the zeta integral for Iwahori spherical vector by using a Casselman-Shalika type formula of Li [Li], which was reported in annual work shop at RIMS in 2004.

3 Archimedean factors

As is seen in the previous section, $p$-adic story is completely similar to the $GL_{2}$-case. No new difficulties come out for $U(3)$. However even for this small group, archimedean factor is hard to handle. In fact we can not mimic Shalika’s idea over archimedean places. So we have to find other ways. Here we appeal to a very direct method. That is to compute out the zeta integral by using an explicit formula for Whittaker functions. This strategy is not so smart nor elegant, but sometimes powerful and useful. Gross and Kudla [Gr-Ku] adopted the strategy to compute the ramified factor of the Garrett integral to reduce it to some Igusa local zeta when one of three cusp form has Iwahori level structure. Over archimedean places, Moriyama [Mo], Ishii studied the Novodvorsky integral for $GSp(4)$, and the author [Is] a Shimura type integral for $U(2,1)$ discovered by Shintani [Shi].

We again divide the story into three steps. The crucial step is the first one, where we compute the $A_{\infty}$-radial part of Whittaker function corresponding to the minimal/corner $K_{\infty}$-type vectors in discrete series /principal series representations.

**Step 1**: Explicit formula for the minimal $K_{\infty}$-type Whittaker functions.
Again by nature of Whittaker functions, their $A_\infty$-radial part is essencial. Note $K_\infty$ is isomorphic to $U(2) \times U(1)$. So the functions are of vector-valued in the representation space of $K_\infty$-type. Fixing a realization, we can expand the $A_\infty$-radial part with respect to the basis. And the coefficient functions can be determined by solving the system of difference-differential equations. Koseki and Oda obtained an explicit formula for the group $SU(2, 1)$. We record a $U(2, 1)$-version, which has cleaner form to handle easier, by the Gel'fand-Zetlin realization. For our group $U(2, 1)$, the representations admitting Whittaker model is "large" discrete series or principal series representations. We omit the principal series case.

**Theorem 5 ([K-O], [I])** Let $\pi_\infty$ be a "large" discrete series representation $\pi_\Lambda$ with Harish-Chandra parameter $(\Lambda_1, \Lambda_2, \Lambda_3)$, i.e. $\Lambda_1 > \Lambda_3 > \Lambda_2$. If the Whittaker function $W$ for $\pi_\Lambda$ has the minimal $K_\infty$-type, this Whittaker vector is written as

$$W\left(\begin{pmatrix} a & 1 \\ 1 & a^{-1} \end{pmatrix}\right) = \sum_{\Lambda_1 \geq k \geq \Lambda_2} c_k \cdot a^{\Lambda_1-a_2-\frac{1}{2}} W_{0,k-\Lambda_1-\Lambda_2+\Lambda_3}(2\sqrt{b}a) \times \left(\left. a^{\Lambda_1, \Lambda_2, k}\right| \otimes 1_{A_3} \right).$$

Here $c_k$ and $b$ are constants and $|^{\Lambda_1, \Lambda_2}|$ stands for the Gel'fand-Zetlin base for $U(2)$-representation.

**Step 2**: Recursion relations among arbitrary $K_\infty$-type $Z_\infty(s; W, \Phi^{(s)}_{\xi})$.

By the branching rule of $U(2)$-module, we can see

$$Z_\infty(s; W, \Phi^{(s)}_{\xi}) = 0 \text{ unless } \Lambda_1 \geq m - \Lambda_3 \geq \Lambda_2.$$

Here $m$ is the parameter of Hecke character $\xi_\infty(\delta) = |\delta|_{\xi}^{t} \left(\frac{\delta}{|\delta|}\right)^{m}$. Moreover when the $K_\infty$-type of Whittaker function $W$ is $[\Lambda_1 + a, \Lambda_2 - b; \Lambda_3 - a + b]$, the $K_\infty$-type of section $\Phi^{(s)}_{\xi}$ should be $[m - \Lambda_3 + a - b, \Lambda_3 - a + b]$, if not the zeta integral vanishes. Therefore most of the members of family $\{Z_\infty(s; W, \Phi^{(s)}_{\xi})\}$ are zero-function. Among the non-trivial $Z_\infty(s; W, \Phi^{(s)}_{\xi})$'s there are recursive relations, which is inherited from ones of $K_\infty$-finite Whittaker functions deduced from differential equations.

**Step 3**: Normalization of Eisenstein series part.

We go back to principal series of $H_\infty \cong U(1, 1)$ and consider the intertwiner

$$A(s; \xi, w) : \text{Ind}_{(B \cap H)_\infty}^{H_\infty}(\xi_\infty \otimes e^{2s} \otimes 1_N) \rightarrow \text{Ind}_{(B \cap H)_\infty}^{H_\infty}(\xi_\infty^{-1} \otimes e^{-2s} \otimes 1_N).$$

We normalize this intertwiner following Langlands, Arthur and Shahidi. Put

$$A^*(s; \xi, w) := \frac{\varepsilon(s; \xi, \psi)(E_{B,\infty}(s; \xi))}{E_{B,\infty}(s + 1; \xi)} A(s; \xi, w)$$

then we have local functional equation of "Eisenstein series"

$$A^*(-s; \xi^{-1}, w) \cdot A^*(s; \xi, w) = Id.$$
Moreover we take natural sections
\[ \Phi^2_{\xi}(s; \ast) := L^r_{E, \infty}(s; \xi) \cdot \Phi_{\xi}(s; \ast), \]
where \( L^r_{E, \infty}(s; \xi) \) is the archimedean factor of Hecke \( L \) modified by Harish-Chandra c-function and \( \Phi_{\xi}(s; \ast) \) is a standard section normalized by \( \Phi_{\xi}(-; e) = 1 \). Then we have symmetrized functional equation
\[ A^*(s; \xi, w) \Phi^\#_{\xi}(s) = \epsilon(s; \xi, \psi) \cdot \Phi_{\overline{\xi}^{-1}}^b(-s). \]

Now we define the archimedean \( L \)-factor \( L_{\infty}(s; \pi_{\infty} \otimes \xi_{\infty}) \) as the "GCD" of the family of zeta integrals for \( K_{\infty} \)-finite Whittaker vectors and the natural sections. Then the above argument gives the following result.

**Theorem 6** The archimedean factor \( L_{\infty}(s; \pi_{\infty} \otimes \xi_{\infty}) \) for the "large" discrete series representation \( \pi_{\infty} = \pi_{\Lambda} \) with Harish-Chandra parameter \( (\Lambda_1, \Lambda_2, \Lambda_3) \) and a Hecke character \( \xi \) with parameter \((t, m) \in \mathbb{C} \times \mathbb{Z}\) is given as follows.

\[
2^{s} \Gamma(s+t+\Lambda_1-\frac{m}{2}) \Gamma(s+t+\Lambda_2+\frac{1}{2}) \left\{ \begin{array}{ll}
\Gamma(s+t-\Lambda_3-\Lambda_1+\frac{3m}{2}) & \text{when } m \geq \Lambda_3 \text{ and } m \geq \Lambda_1 \\
\Gamma(s+t-\Lambda_3-\Lambda_2+\frac{1}{2}) & \text{when } \Lambda_2 \geq m \geq \Lambda_3 \\
\Gamma(s+t-\Lambda_2+\frac{1}{2}) & \text{when } \Lambda_1 \geq m \geq \Lambda_2 \\
\Gamma(s+t-\Lambda_1+\frac{1}{2}) & \text{when } \Lambda_3 \geq m \geq \Lambda_1 \\
\Gamma(s+t-\frac{m}{2}) & \text{when } \Lambda_3 \geq m \text{ and } \Lambda_1 \geq m
\end{array} \right.
\]
supposing \( \Lambda_1 + \Lambda_3 \geq m \geq \Lambda_2 + \Lambda_3 \).

We reported archimedean local functional equation in the occasion of the talk in Jan/21. However some serious mistake was found afterward and has not been removed so far. We would like to reconsider this probrem in near future.

**References**


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