Cohomological Induction on $Sp\,(4,\mathbf{R})$ and Maass Lift

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This is the report on another item belonging to the patchwork of joint work with Ralf Schmidt trying to understand the Maass lift from Jacobi to Siegel forms in a representation theoretic way à la Pyatetski Shapiro [PS1,2]. In [Be] and [BeS2] we developed a recipe (using a certain intertwining operator) to lift a discrete series representation $\pi^+_{m,k}$ of the Jacobi group $G^J = SL(2,\mathbf{R}) \ltimes Heis(\mathbf{R})$ to a discrete series representation σ^+_k of the symplectic group $G_0 = Sp\,(4,\mathbf{R})$ reflecting the Maass lift from a holomorphic Jacobi form $f \in J_{k,1}$ to a holomorphic Siegel form $F \in M_k(\Gamma_2), \Gamma_2 = Sp(4,\mathbf{Z})$. In [S] Schmidt characterized in generality the "special" representations of G_0 coming in a unique way by the lift from the representations π^J of G^J which were classified in [BeS1].

Now, having done the holomorphic Jacobi forms, the next step is the question where Skoruppa's skew-holomorphic Jacobi forms lift to. Here, as a side effect of a generalization of Borcherds' theta lift, Bruinier stated in [Br] Theorem 5.8 a theta lift from the space $J^{*cusp}_{3,m}$ of skew-holomorphic Jacobi cusp forms of weight 3 and index m to certain (1,1)-cohomology classes of the space $\mathbf{H}_2/\Gamma_2^{(m)}$, where $\mathbf{H}_2$ is the Siegel upper half plane of degree 2 and $\Gamma_2^{(m)}$ the paramodular group of level m. Bruinier further remarks that the holomorphic $f \in J^{cusp}_{3,m}$ go similarly by the usual Maass lift to (3,0)-cohomology classes. This last fact fits easily in a representation theoretic interpretation, as (3,0)-classes may be represented by holomorphic differential forms of degree 3 which in turn belong to holomorphic Siegel modular forms of weight 3. Thus, by the usual characterization of holomorphic automorphic forms as lowest weight vectors for discrete series representations, behind this lies the fact explained in [BeS2] that the discrete series representations of G^J can be lifted to certain discrete series representations of G_0. This note is meant to give a similar explanation for the skew-case where the construction of unitary representations of G_0 by cohomological induction comes into effect.

It is to be remarked that some elements of an older paper by Weissauer [W] on differential forms for subgroups of $Sp(4,\mathbf{Z})$ reappear here in the light of the description of the cohomological induction given in the meantime e.g. in the articles by Zierau [Z] and Barchini [B]. Moreover, the methods used here are in close relation to those used by Oda and his school (see in particular [OT]).
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1. An overview

As explained in [BeS1], the representation

$$\pi^-_{m,k} = \pi^m_{SW} \otimes \pi^-_{k-1/2},\ m,k \in \mathbf{N},$$

of the Jacobi group $G^J = SL(2,\mathbf{R}) \times Heis(\mathbf{R})$ "belongs" to the skew-holomorphic Jacobi form $f \in J^*_{k,m}$. And as explained in [BeS2] and [S], this representation lifts to a representation σ^-_k of $G_0 = Sp\,(4,\mathbf{R})$ having the minimal K_0 - type $\Lambda = (k-1, 1-k)$, $K_0 \simeq U(2)$ the usual maximal compact subgroup of G_0. In the notation of Knapp-Vogan [KV] this is (using Proposition 10.24) uniquely related to a cohomologically induced representation

$$A_{\mathbf{q}}(\lambda)$$

resp. via [Z] Theorem 5.2 in the framework of Zierau and Barchini to a representation given by the usual left action on a cohomology space

$$H^1(G_0/L_0, \mathcal{L}_\chi).$$

This space can be injected by a Penrose transformation $\mathcal{P}$ into another space of sections of a bundle $\mathcal{E}_{\chi'}$

$$\mathcal{C}^\infty(G_0/K_0, \mathcal{E}_{\chi'})$$

over the Siegel space $\mathbf{H}_2 = G_0/K_0$, which can be related to a space of (1,1)-forms on $\mathbf{H}_2$ and thus gives the desired representation theoretic background for Bruinier's result.
To explain the notation used here, we will describe the following geometric picture.

2. A special double fibration

We use the notation from [BeS2] to describe the usual Cartan decomposition

$$\begin{array}{rcl}
\mathbf{g} & = & \mathbf{g}_0 \otimes \mathbf{C} \\
 & = & \mathbf{k} + \mathbf{p} = < Z, Z', N_\pm > + < X_\pm, P_{1\pm}, P_{0\pm} > \\
 & = & \mathbf{h} + \oplus_{\alpha\in\Delta} \mathbf{g}_\alpha, \\
\mathbf{h} & = & < Z, Z' >, \qquad \Delta = \{\pm(1,-1), \pm(2,0), \pm(1,1), \pm(0,2)\}.
\end{array}$$

Chosing as simple roots $\Pi = \{(1,1),(0,-2)\}$ we get the parabolic subalgebra $\mathbf{q}$ of $\mathbf{g}$ belonging to (1,1) with the Levi decomposition

$$\mathbf{q} = \mathbf{l} + \mathbf{u} = < Z, Z', P_\pm > + < X_+, N_+, P_{0-} > .$$

(A list of the K-conjugacy classes of θ-stable parabolic subalgebras of $\mathbf{g}$ is to be found in Miyazaki [M]. As will become clear later, this choice of $\mathbf{q}$ is just the right one to produce by cohomological induction the representation σ_k^- having the right K-types.)

Remark 1: The associated real Levi subgroup

$$L_0 = \{g \in G,\ Ad(g)\mathbf{q} \subset \mathbf{q}\}$$

(with $\mathbf{l}_0 = \mathrm{Lie}\, L_0$, s.t. $\mathbf{l} = \mathbf{l}_0 \otimes \mathbf{C}$) is isomorphic to $U(1,1)$:
We take the injection

$$j : U(1,1) \hookrightarrow Sp\,(4, \mathbf{R}) = G_0$$

given by

$$A = X + iY \longmapsto \begin{pmatrix} X & -SY \\ SY & SXS \end{pmatrix}, \quad S = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}.$$

Then one has for

$$\begin{aligned} \mathbf{u}(1,1) &= \left\{ \begin{pmatrix} i\alpha & \beta + i\gamma \\ \beta - i\gamma & i\delta \end{pmatrix} : \quad \alpha, \beta, \gamma, \delta \in \mathbf{R} \right\} \\ &= < U_1, U_2, U_3, U_4 >, \end{aligned}$$

$$U_1 = \begin{pmatrix} i & \\ & 0 \end{pmatrix}, U_2 = \begin{pmatrix} 0 & \\ & i \end{pmatrix}, U_3 = \begin{pmatrix} & 1 \\ 1 & \end{pmatrix}, U_4 = \begin{pmatrix} & i \\ -i & \end{pmatrix},$$

i.e. with the notation of [BeS2]

$$\begin{aligned} j(U_1) &= -iZ = G - F = \begin{pmatrix} & & -1 & \\ & & & \\ 1 & & & \\ & & & \end{pmatrix}, \\ j(U_2) &= iZ' = R - R' = \begin{pmatrix} & & & \\ & & & 1 \\ & & & \\ & -1 & & \end{pmatrix}, \\ j(U_3) &= P_{1+} + P_{1-} = P + P' = \begin{pmatrix} & 1 & & \\ 1 & & & \\ & & & -1 \\ & & -1 & \end{pmatrix}, \\ j(U_4) &= -i(P_{1+} - P_{1-}) = Q + Q' = \begin{pmatrix} & & & 1 \\ & & 1 & \\ & 1 & & \\ 1 & & & \end{pmatrix}. \end{aligned}$$

From here, we easily see

$$j(\mathbf{u}(1,1)) = \mathbf{l}_0.$$

Further on, we take over from the construction 4.3 of θ-stable parabolics in Vogan [V] p.231, that our L_0 may be characterized by

$$L_0 = L_0(\lambda) = \{g \in G_0,\ Ad^*(g)(\lambda) = \lambda\},$$

where here

$$\lambda = (k, -k) \in i\mathbf{t}_0^*, \quad \mathbf{t}_0 =< -j(U_1), j(U_2) > .$$

And using the commutation relations, one easily verifies that $\mathbf{l}_0$ is the centralizer of $j(U_1) + j(U_2)$ in $\mathbf{g}_0$.

Now, we put

$$D := G_0/L_0$$

and by the general theory this homogeneous space is a subvariety of

$$Z = G/Q,$$

Q the parabolic subgroup of $G = Sp\,(4, \mathbf{C})$ with $\mathrm{Lie}\, Q = \mathbf{q}$.

Remark 2: The usual injection

$$j' : U(2) \longrightarrow K_0 \subset Sp(4, \mathbf{R}) = G_0$$

is given by

$$A = X + iY \longmapsto \begin{pmatrix} X & -Y \\ Y & X \end{pmatrix}.$$

Then one has for

$$\begin{aligned}
\mathbf{u}(2) &= \{\begin{pmatrix} i\alpha & \beta + i\gamma \\ -\beta + i\gamma & i\delta \end{pmatrix} : \quad \alpha, \beta, \gamma, \delta \in \mathbf{R}\,\} \\
&= < U_1, U_2, V_3, V_4 >, \quad V_3 = \begin{pmatrix} & 1 \\ -1 & \end{pmatrix}, V_4 = \begin{pmatrix} & i \\ i & \end{pmatrix}, \\
&= < V_1 > \oplus < V_2, V_3, V_4 >, \quad V_1 = U_1 + U_2 = \begin{pmatrix} i & \\ & i \end{pmatrix}, \\
&= < V_1 > \oplus\, \mathbf{su}(2), \qquad V_2 = U_1 - U_2 = \begin{pmatrix} i & \\ & -i \end{pmatrix},
\end{aligned}$$

i.e.

$$
\begin{aligned}
j'(U_1) &= j(U_1) = G - F = \begin{pmatrix} & & -1 & \\ & & & \\ 1 & & & \\ & & & \end{pmatrix}, \\
j'(U_2) &= -j(U_2) = R' - R = \begin{pmatrix} & & & \\ & & & -1 \\ & & & \\ & 1 & & \end{pmatrix}, \\
j'(V_3) &= N_+ + N_- = P' - P = \begin{pmatrix} & 1 & & \\ -1 & & & \\ & & & 1 \\ & & -1 & \end{pmatrix}, \\
j'(V_4) &= -i(N_+ - N_-) = Q' - Q = \begin{pmatrix} & & & -1 \\ & & -1 & \\ & 1 & & \\ 1 & & & \end{pmatrix}.
\end{aligned}
$$

Remark 3: Here, we see

$$\mathbf{t}_0 := \mathbf{l}_0 \cap \mathbf{k}_0 \simeq \mathbf{u}(1,1) \cap \mathbf{u}(2) \simeq \mathbf{u}(1) \oplus \mathbf{u}(1)$$

i.e.

$$\mathbf{t} = \mathbf{t}_0 \otimes \mathbf{C} = < Z, Z' > = \mathbf{h}.$$

Later it will become important that one has

$$\mathbf{t}_0 = < j(V_1) = j'(V_2), j(V_2) = j'(V_1) > .$$

Abbreviating $T_0 := L_0 \cap K_0$, we have the double fibration

$$D := G_0/L_0 \xleftarrow{\mu} Y := G_0/T_0 \xrightarrow{\tau} X = G_0/K_0 = \mathbf{H}_2.$$

Remark 4: The fibers of μ are

$$L_0/T_0 \simeq U(1,1)/(U(1) \times U(1)) \simeq \mathbf{E}_1,$$

the open unit disc, and the fibers of τ

$$K_0/T_0 \simeq U(2)/(U(1) \times U(1)) \simeq SU(2)/U(1) \simeq \mathbf{P}^1(\mathbf{C})$$

the one-dimensional complex projective space.
Here, as usual, we take

$$
\begin{array}{ccc}
U(1) & \hookrightarrow & SU(2) \\
e^{i\psi} & \longmapsto & \begin{pmatrix} e^{i\psi} & \\ & e^{-i\psi} \end{pmatrix} =: t(\psi),
\end{array}
$$

and

$$SU(2) = \{\, g = \begin{pmatrix} \alpha & \beta \\ -\bar{\beta} & \bar{\alpha} \end{pmatrix}, \alpha, \beta \in \mathbf{C}, |\alpha|^2 + |\beta|^2 = 1\}$$

acts on $\mathbf{P}^1(\mathbf{C})$ by

$$(g, z = (u : v)) \longmapsto g(z) = ((\alpha u + \beta v) : (-\bar{\beta} u + \bar{\alpha} v)).$$

Then the isotropy group of $z_o = (0 : 1)$ is just

$$\{t(\psi) = \begin{pmatrix} e^{i\psi} & \\ & e^{-i\psi} \end{pmatrix}\} \simeq U(1).$$

3. The representations of $U(2)$

As well known, the equivalence classes of representations τ_N^0 of $SU(2)$ may be parametrized by the natural numbers $N \in \mathbf{N}_0$ and the standard model for τ_N^0 is given on the space V_N of homogeneous polynomials P in two variables u and v by

$$\tau_N^0(g_0)P((u,v)^t) = P(g_o^{-1}(u,v)^t).$$

That is, we have here

$$\tau_N^0(t(\psi)) = \ \mathrm{diag}(e^{-iN\psi}, \ldots, e^{iN\psi}).$$

The classes of representations τ_Λ of $U(2)$ may be parametrized by pairs $(l, N) \in \mathbf{Z} \times \mathbf{N}_0$, where

$$\begin{aligned} \tau_\Lambda(e^{i\varphi}E_2) &= e^{ilvarphi}E_{N+1}, \\ \tau_\Lambda(t(\psi)) &= \tau_N^0(t(\psi)). \end{aligned}$$

That is, (l, N) can be seen as weights belonging to $V_1 = U_1 + U_2, V_2 = U_1 - U_2$ in the notation introduced above. Equivalently, as parameters one can take pairs

$$\Lambda \in \Delta = \{(\lambda, \lambda') \in \mathbf{Z}^2, \lambda \geq \lambda'\}$$

belonging to (U_1, U_2), i.e.

$$l = \lambda + \lambda', N = \lambda - \lambda' \quad \text{resp.} \quad \lambda = (l+N)/2, \lambda' = (l-N)/2$$

and one has

$$\tau_\Lambda(\begin{pmatrix} e^{i\vartheta} & \\ & e^{-i\vartheta'} \end{pmatrix}) = \mathrm{diag}(e^{i(\lambda'\vartheta + \lambda\vartheta')}, \ldots, e^{i(\lambda\vartheta + \lambda'\vartheta')}).$$

4. A special representation and its line bundles

In section 2 we are in the situation of a double fibration with contractible fibers for μ on the one side and a Stein space X on the other, so that the usual formalism of the Penrose transform associating sections of an appropriate bundle $\mathcal{E}_{\chi'}$ on X as in [Z] and [B] to cohomology classes belonging to D applies. We start by the cohomology of a holomorphic complex line bundle $\mathcal{L}_\chi$ over $D = G_0/L_0$

$$H^p(D, \mathcal{L}_\chi)$$

constructed from the one-dimensional $(L_0, \mathbf{q})-$representation χ on $\mathbf{C}_\chi = \mathbf{C}$ which by the general theory (as for instance in [Z] p.118) can be understood as the sheaf cohomology for the sheaf of germs of sections of the bundle $\mathcal{L}_\chi$ or as the Dolbeault cohomolgy of the complex of smooth (0,p)-forms with values in the fiber $\mathbf{C}_\chi$ of $\mathcal{L}_\chi$

$$A^p(D, \mathcal{L}_\chi) = \{\mathcal{C}^\infty(G_0) \otimes \mathbf{C}_\chi \otimes \wedge^p \overline{\mathbf{u}}\}^{L_0}$$

where the identification $\overline{\mathbf{u}} \simeq \mathbf{u}^*$ has been made. Theorem 5.2 from [Z] tells that $H^p(D, \mathcal{L}_\chi)$ is an admissible representation of G_0 and the maximal globalization of the underlying Harish-Chandra module

$$\mathcal{R}^p_{\mathbf{q}}(\mathbf{C}_{\tilde{\chi}}), \quad \tilde{\chi} = \chi - 2\rho(\mathbf{u}),$$

ρ the half sum of the roots from the set

$$\Delta(\mathbf{u}) = \{(2,0), (1,-1), (0,-2)\}$$

of roots coming into $\mathbf{u}$. And moreover, if s is the complex dimension of a maximal compact subvariety of D and

$$(*) \qquad < \chi + \rho, \beta > \quad > 0 \qquad \text{for all} \quad \beta \in \Delta(\mathbf{u})$$

then we have

$$H^p(D, \mathcal{L}_\chi) = 0 \qquad \text{for}\, p \neq s$$

and this is an irreducible representation for $p = s$. Furtheron Zierau describes a Penrose transform

$$\mathcal{P} : H^s(D, \mathcal{L}_\chi) \longrightarrow \mathcal{C}^\infty(G_0/K_0, \mathcal{E}_{\chi'})$$

which under the dominance condition (*) above comes out as an injection (Theorem 7.2 in [Z] resp. Theorem 2.1 in [B]). As decribed in [B] p.153/4 $\mathcal{E}_{\chi'}$ is the bundle on G_0/K_0 associated to the K_0-representation $E_{\chi'}$ which by the Borel-Bott-Weil theorem is given by

$$H^s(K_0/(K_0 \cap L_0), \check{\mathcal{L}}_{\tilde{\chi}}),$$

where the symbol $\check{\mathcal{L}}_{\tilde{\chi}}$ stands for the pullback over the holomorphic injection

$$K_0/(K_0 \cap L_0) \hookrightarrow G_0/L_0$$

of the original bundle $\mathcal{L}_\chi \to G_0/L_0$, we started with.
In the case at hand here, we have

$$s = \dim_{\mathbf{C}} K_0/(K_0 \cap L_0) = 1$$

and we get as our main tool the following result.

Proposition: We have an injection given by the Penrose transform

$$\mathcal{P} : H^s(D, \mathcal{L}_\chi) \longrightarrow \mathcal{C}^\infty(G_0/K_0, \mathcal{E}_{\chi'})$$

where

$$\chi = (k, -k) \qquad \text{and} \qquad \chi' = (k-1, 1-k)$$

indicate the parameters fixing the representation of L_0 resp K_0 used to construct the bundle $\mathcal{L}_\chi$ resp $\mathcal{E}_{\chi'}$.

Proof: By Schmidt's discussion of the K_0-types of the representation σ_k^- of G_0 in [S], we are looking for a representation with minimal K_0-type $\tau_\Lambda, \Lambda = (k-1, 1-k), k \geq 3$. From [KV] Proposition 10.24 we conclude that using the notation from section 2 we have to take

$$A_{\mathbf{q}}(\lambda) \qquad \text{with} \qquad \Lambda = \lambda + 2\rho(\mathbf{u} \cap \mathbf{p}),$$

i.e. in our case with

$$\mathbf{q} = \mathbf{l} + \mathbf{u} = < Z, Z', P_\pm > + < X_+, N_+, P_{0-} > .$$

we have

$$\lambda = \Lambda - (2, -2) = (k-3, 3-k).$$

And by the result from Zierau, cited above, we look here at

$$H^1(D, \mathcal{L}_\chi)$$

with

$$\chi = \lambda + 2\rho(\mathbf{u}) = \lambda + (3, -3) = (k, -k).$$

Here our χ fulfills the dominance condition (*) given above. By the general procedure, we have to pull back to $\mathbf{P}^1 \simeq K_0/(K_0 \cap L_0)$ the bundle $\mathcal{L}_\chi$ over G_0/L_0 given by

$$\chi(r(\theta)r'(\theta')) = \chi(j(\begin{pmatrix} e^{i\vartheta} & \\ & e^{-i\vartheta'} \end{pmatrix})) = e^{ik(\vartheta - \vartheta')}.$$

As

$$r(\vartheta)r'(\vartheta') = \begin{pmatrix} \cos\vartheta & & \sin\vartheta & \\ & \cos\vartheta' & & \sin\vartheta' \\ -\sin\vartheta & & \cos\vartheta & \\ & -\sin\vartheta' & & \cos\vartheta' \end{pmatrix} \in G_0$$

is the image of the element

$$\begin{pmatrix} e^{-i\vartheta} & \\ & e^{-i\vartheta'} \end{pmatrix} \in U(2)$$

by the embedding $j' : U(2) \longrightarrow G_0$ from Remark 2 in section 2, the pullback bundle $\check{\mathcal{L}}_{\check{\chi}}$ on $\mathbf{P}^1$ is constructed using the character

$$\check{\chi}(\begin{pmatrix} e^{i\vartheta} & \\ & e^{i\vartheta'} \end{pmatrix}) = e^{-ik(\vartheta-\vartheta')},$$

the cohomology

$$H^1(\mathbf{P}^1, \check{\mathcal{L}}_{\check{\chi}})$$

carries the representation τ^0_{2k-2} of $SU(2)$ and (see section 3) a representation τ_Λ of $U(2)$ with parameters $l = 0$, $N = 2k-2$, i.e. with $\Lambda = (k-1, 1-k)$. Thus, by Theorem 7.2 from [Z], we come to the bundle $\mathcal{E}_{\chi'}$ on $G_0/K_0 = \mathbf{H}_2$ constructed from the representation $\chi' = \tau_\Lambda$ of K_0 with $\Lambda = (k-1, 1-k)$.

5. Siegel forms and representations

As done in Weissauer [W] p.105, it is natural to associate to a differential form η of type (p,q) on $\mathbf{H}_2$ a vector valued modular form

$$f_\eta : \mathbf{H}_2 \longrightarrow V^{(p,q)}.$$

Here

$$V^{(p,q)} = \wedge^p S^2(\mathbf{C}^2) \otimes \wedge^q S^2(\bar{\mathbf{C}}^2)$$

is the representation space built as usual from the natural representation of $GL(2,\mathbf{C})$ on $\mathbf{C}^2$. $S^2(\mathbf{C}^2) \simeq V_2$ is thought of as spanned by

$$d\tau \simeq u^2, \quad dz \simeq uv, \quad d\tau' \simeq v^2,$$

where

$$Z = \begin{pmatrix} \tau & z \\ z & \tau' \end{pmatrix} \in \mathbf{H}_2 = G_0/K_0.$$

By restriction to $U(2)$ we get the representation τ_Λ with $\Lambda = (2,0)$. Similarly $S^2(\bar{\mathbf{C}}^2)$ has weight $\Lambda = (0,2)$. Reducing the tensor product above as a $U(2) \simeq K_0$-representation, we have

$$V^{(1,1)} = V_{\tau_{(2,-2)}} + V_{\tau_{(1,-1)}} + V_{\tau_{(0,0)}},$$

fitting in with the result from the Proposition of the last section, where for $k = 3$ we just came up with a bundle over $\mathbf{H}_2$ belonging to the representation $\tau_{(2,-2)}$ of K_0. So finally, we have a map from a skew-holomorphic Jacobi form to a cohomology class in $H^1(D, \mathcal{L}_\chi)$ and from there to a section of a subbundle of the bundle of (1,1)-forms on $\mathbf{H}_2$.

This encourages the conjecture, that as much as holomorphic differential forms belong to holomorphic discrete series representations, at least in this case (1,1)-forms belong to cohomologically induced (not discrete series) representations.

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