STRONG GENERALIZED HOLOMORPHIC PRINCIPAL BUNDLES

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ABSTRACT. We introduce the notion of a strong generalized holomorphic (SGH) fiber bundle and develop connection and curvature theory for an SGH principal G-bundle over a regular generalized complex (GC) manifold, where G is a complex Lie group. We develop a de Rham cohomology for regular GC manifolds, and a Dolbeault cohomology for SGH vector bundles. Moreover, we establish a Chern-Weil theory for SGH principal G-bundles under certain mild assumptions on the leaf space of the GC structure. We also present a Hodge theory along with associated dualities and vanishing theorems for SGH vector bundles. Several examples of SGH fiber bundles are given.

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1. INTRODUCTION

Generalized complex (GC) geometry presents a unified framework for a range of geometric structures whose two extreme cases are complex and symplectic structures. The notion was introduced by Hitchin [16] and developed to a large extent by his doctoral students Gualtieri [14, 15] and Cavalcanti [9]. The appropriate generalization of holomorphic bundles in complex geometry to GC geometry has received much attention [14, 15, 17, 30, 22].

The study of principal bundles or vector bundles involves four basic differential geometric aspects, namely: (1) The exploration of connection and curvature, (2) Chern-Weil theory and characteristic classes, (3) Hodge theory and its associated dualities and vanishing theorems, and (4) Deformation theory. Notably, in the case of holomorphic principal bundles or vector bundles, these four aspects reveal rich geometric properties [3, 8, 18, 19, 20, 21, 29]. Naturally, one can ask the following:

Question 1.1.

- (1) What kind of vector or principal bundle theory arises within GC geometry?
- (2) How are these four classical geometric components represented within the framework of GC geometry?

In [14, 15], Gualtieri introduced generalized holomorphic (GH) vector bundles, which are complex vector bundles defined over a GC manifold equipped with a Lie algebroid connection. Wang further extended this in [30], introducing GH principal bundles by extending the structure group action to an exact Courant algebroid. These provide an answer to (1) in Question 1.1. Additionally, in [31], Wang explored the deformation of GH vector bundles, covering one of the four geometric aspects. However, the absence of a generalized complex structure (GCS) on the total space of the bundle in these notions hindered the investigation of the remaining three components. Recently, in [22], Lang et al. tried to address this by considering a new concept of GH vector bundles equipped with a GCS on the total space. Their GCS on the total space is locally a product the GCS on the base and the fiber. They also introduced the Atiyah sequence of such

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bundles and defined its splitting as a generalized holomorphic connection. This new notion of GH vector bundle is more rigid than the notion due to Gualtieri [14, 15] and Hitchin [17], and yields a strict subclass. But, it has the potential of being more amenable to methods from complex geometry.

In this paper, we generalize the work of [22] on vector bundles to fiber and principal bundles. To distinguish these bundles from the earlier notions due to Gualtieri and Wang [30], we refer to our bundles as *strong generalized holomorphic* or *SGH* bundles. A regular GCS induces a regular foliation with symplectic leaves and a transverse complex structure. The SGH bundles are intuitively characterized by the fact they are flat along the leaves and transversely holomorphic. However, they form a bigger category than the category of holomorphic bundles on the leaf space (when the leaf space is a manifold or an orbifold), see Examples 14.6, and 14.7.

Both the base and fiber of an SGH fiber bundle are GC manifolds, and the total space admits a GCS that is locally a product GCS derived from the base and the fiber, see Definition 3.1. In the context of vector bundles, SGH vector bundles correspond precisely to the GH vector bundles of Lang et al. (cf. [22]). Similarly, in the realm of principal bundles, they are a subclass of the GH principal bundles analyzed by Wang (cf. [30, Example 4.2]).

The main contribution of this article is in adapting the methods of complex geometry to introduce a suitable Dolbeault cohomology theory for SGH vector bundles and in using it to develop suitable generalizations of Chern-Weil theory and Hodge theory for these bundles. To do so, an assumption that the leaf space of the symplectic foliation is a complex (Kähler) orbifold is often necessary. A more detailed outline of the paper is given below.

In Section 2, we describe the basic facts on GCS and generalized holomorphic (GH) maps. In Sections 3-4, we introduce the notions of SGH fiber bundle and SGH principal bundle.

In Section 5, we follow Atiyah's approach to defining holomorphic connection of a holomorphic principal bundle [3], to construct the Atiyah sequence of an SGH principal G-bundle P over a regular GC manifold M, where G is a complex Lie group:

$$0 \longrightarrow Ad(P) \longrightarrow At(P) \longrightarrow \mathcal{G}M \longrightarrow 0.$$

Here, $\mathcal{G}M$ is the GH tangent bundle of M, Ad(P) is the adjoint bundle of P, and At(P) is the Atiyah bundle of P. A GH connection on P is a GH splitting of the above short exact sequence, and the Atiyah class is the obstruction to such a splitting; see Definition 5.4 and Theorem 5.5. Furthermore, in Section 6, a la Atiyah, we establish that the Atiyah class of an SGH vector bundle and the Atiyah class of its associated SGH principal bundle agree up to a sign in Theorem 6.4.

In Section 7, we discuss the leaf space associated to the regular symplectic foliation \mathscr{S} with a transverse complex structure of a GCS. In general, the leaf space M/\mathscr{S} might

lack the Hausdorff property, as illustrated in 7.6. Nonetheless, assuming M/\mathscr{S} is a smooth orbifold, we provide a structured description of \mathscr{S} in Theorem 7.3. Moreover, in Section 8, utilizing Theorem 7.3, we develop the de Rham cohomology $H_{0}^{\bullet,\star}(M)$ for regular GC manifolds in Proposition 8.8, and the Dolbeault cohomology $H_{d_L}^{\bullet,\star}(M, E)$ of an SGH vector bundle E in Corrollary 8.10. This leads to the notion of the curvature of a smooth generalized connection (see Definition 5.7) on an SGH principal bundle in Section 8.2, and also, provides a crucial relationship between the curvature and its Atiyah class, as follows:

Theorem. (Theorem 8.12) For an SGH principal *G*-bundle *P* over a regular GC manifold *M*, with *G* as a complex Lie group and M/\mathscr{S} as a smooth orbifold, the (1,1)-component of the curvature of a smooth generalized connection of type (1,0) on *P*, which is constant along the leaves, corresponds to the Atiyah class of *P* in $H^1(M, \mathcal{G}^*\mathbf{M} \otimes_{\mathcal{O}_M} \mathbf{Ad}(\mathbf{P})).$

In Section 9, we establish the generalized Chern-Weil homomorphism in Definition 9.1 using the generalized connection of Theorem 8.12, and define the generalized characteristic class.

In Section 10, we develop the theory of smooth generalized connection and its curvature. We also introduce transverse connection and its curvature in Definition 10.11 and present a Chern-Weil theory of SGH vector bundles similar to Section 9. In particular, we prove that the existence of a GH connection on an SGH bundle is the same as the existence of a GH connection on its associated SGH principal bundle; see Theorem 10.21. Furthermore, we provide an analogue of the holomorphic Picard group and exponential sequence in Section 11.

In Section 12, we develop generalized versions of classical results such as Serre duality and Poincaré duality. We also introduce a Hodge decomposition for the *D*-cohomology and d_L -cohomology (see Section 8.1) of a regular GC manifold. We establish the following result.

Theorem. (Theorem 12.4) For any compact regular GC manifold M of type k, given that M/\mathscr{S} is a smooth orbifold, the following holds.

(1) $H_D^{\bullet}(M) \cong (H_D^{2k-\bullet}(M))^*$.

(2)
$$H_{d_L}^{\bullet,\bullet}(M) \cong (H_{d_L}^{k-\bullet,k-\bullet}(M))^*$$
.

(3) If \mathscr{S} is also transversely Kähler, we have, $H_D^{\bullet}(M) = \bigoplus_{p+q=\bullet} H_{d_L}^{p,q}(M)$.

Extending Theorem 12.4, when the coefficient of $H_{d_L}^{\bullet,\star}(M)$ is an SGH vector bundle, we establish a generalized Hodge decomposition in Theorem 12.6 and provide a generalized Serre duality in Theorem 12.7, under the assumption of Theorem 12.4. Additionally, we establish the following vanishing theorem.

Theorem. (Theorem 12.12) For a compact regular GC manifold M of type k, assuming M/\mathscr{S} is a Kähler orbifold, we have the following.

- (1) $H^q(M, (\mathcal{G}^*\mathbf{M})^p \otimes_{\mathcal{O}_M} \mathbf{E}) = 0$ for p + q > k.
- (2) For any SGH vector bundle E' on M, there exists a constant m_0 such that $H^q(M, \mathbf{E}' \otimes_{\mathcal{O}_M} \mathbf{E}^m) = 0$ for $m \ge m_0$ and q > 0 where E be a positive SGH line bundle on M.

In Section 13, we give some criteria on the GCS so that the leaf space of the associated symplectic foliation is a smooth torus, and therefore, satisfies the hypothesis that the leaf space be an orbifold, used in most of our results in previous sections. This is a generalization of a result of Bailey et al. [4, Theorem1.9]. Then, in Section 14, we give a complete characterization of the leaf space of a left invariant GCS on a simply connected nilpotent Lie group and its associated nilmanifolds. Finally, we construct some examples of nontrivial SGH bundles on the Iwasawa manifolds which show that the category of SGH bundles is in general different from the category of holomorphic bundles on the leaf space.

1.1. Notation

- If E denotes an SGH fiber bundle over M, then \mathbf{E} denotes the corresponding sheaf of GH sections of E, and for any open set $U \subseteq M$, we denote the set of GH sections of E over U by $\Gamma(U, \mathbf{E})$ or by $\mathbf{E}(U)$.
- If E denotes a smooth fiber bundle over M, then $C^{\infty}(E)$ denotes the corresponding sheaf of smooth sections of E and for any open set $U \subseteq M$, $C^{\infty}(U, E)$ denotes the set of smooth sections of E over U.
- Given a smooth manifold M, for any open set $U \subseteq M$, $C^{\infty}(U)$ denotes the ring of \mathbb{C} -valued smooth functions on U and C_M^{∞} denotes the sheaf of \mathbb{C} -valued smooth functions over M.

2. Preliminaries

2.1. Generalized complex structure (GCS)

We first start by recalling some basic notions of generalized complex (in short GC) geometry. In this subsection, we shall rely upon [14] and [15] for most of the definitions and results.

Given any 2n-dimensional smooth manifold M, the direct sum of tangent and cotangent bundles of M, which we denote by $TM \oplus T^*M$, is endowed with a natural symmetric bilinear form of signature (2n, 2n)

$$\langle X + \xi, Y + \eta \rangle := \frac{1}{2} (\xi(Y) + \eta(X)).$$
 (2.1)

It is also equipped with the *Courant Bracket* defined as follows.

Definition 2.1. The Courant bracket is a skew-symmetric bracket defined on smooth sections of $TM \oplus T^*M$, given by

$$[X + \xi, Y + \eta] := [X, Y]_{Lie} + \mathcal{L}_X \eta - \mathcal{L}_Y \xi - \frac{1}{2} d(i_X \eta - i_Y \xi), \qquad (2.2)$$

where $X, Y \in C^{\infty}(TM), \xi, \eta \in C^{\infty}(T^*M), [,]_{Lie}$ is the usual Lie bracket on $C^{\infty}(TM)$, and \mathcal{L}_X , i_X denote the Lie derivative and the interior product of forms with respect to the vector field X, respectively.

We are now ready to define the notion of GCS in a 2n-dimensional smooth manifold M in two equivalent ways.

Definition 2.2. (cf. [14]) A generalized complex structure (GCS) is determined by any of the following two equivalent sets of data:

(1) A bundle automorphism \mathcal{J}_M of $TM \oplus T^*M$ which satisfies the following conditions:

(a)
$$\mathcal{J}_M^2 = -1$$

- (b) $\mathcal{J}_M^* = -\mathcal{J}_M$, that is, \mathcal{J}_M is orthogonal with respect to the natural pairing in (2.1)
- (c) \mathcal{J}_M has vanishing Nijenhuis tensor, that is, for all $C, D \in C^{\infty}(TM \oplus T^*M)$,

$$N(C,D) := [\mathcal{J}_M C, \mathcal{J}_M D] - \mathcal{J}_M [\mathcal{J}_M C, D] - \mathcal{J}_M [C, \mathcal{J}_M D] - [C, D] = 0$$

(2) A subbundle, say L_M , of $(TM \oplus T^*M) \otimes \mathbb{C}$ which is maximal isotropic with respect to the natural bilinear form (2.1), involutive with respect to the Courant bracket (2.2), and satisfies $L_M \cap \overline{L_M} = \{0\}$.

In Definition 2.2, the two equivalent conditions are related to each other by the fact that the subbundle L_M may be obtained as the +i-eigenbundle of the automorphism \mathcal{J}_M .

Given any GC manifold (M, \mathcal{J}_M) , we can deform \mathcal{J}_M by a real closed 2-form B, known as a *B*-field transformation, to get another GCS on M,

$$(\mathcal{J}_M)_B = e^{-B} \circ \mathcal{J}_M \circ e^B \quad \text{where} \quad e^B = \begin{pmatrix} 1 & 0 \\ B & 1 \end{pmatrix}.$$
(2.3)

The +i-eigenbundle of $(\mathcal{J}_M)_B$ is

$$(L_M)_B = \{X + \xi - B(X, \cdot) \mid X + \xi \in L_M\}.$$
(2.4)

Let us consider some simple examples of GCS.

Example 2.3. Let (M, J_M) is a complex manifold with a complex structure J_M . Then the natural GCS on M is given by the bundle automorphism

$$\mathcal{J}_M := \begin{pmatrix} -J_M & 0\\ 0 & J_M^* \end{pmatrix} : TM \oplus T^*M \longrightarrow TM \oplus T^*M$$

Its corresponding +i-eigen bundle is

$$L_M = T^{0,1}M \oplus (T^{1,0}M)^*$$
.

Example 2.4. Let (M, ω) be a symplectic manifold with a symplectic structure ω . Then, the bundle automorphism

$$\mathcal{J}_M := \begin{pmatrix} 0 & -\omega^{-1} \\ \omega & 0 \end{pmatrix} : TM \oplus T^*M \longrightarrow TM \oplus T^*M ,$$

gives a natural GCS on M. The +i-eigen bundle of this GCS is

$$L_M = \{ X - i\omega(X) \, | \, X \in TM \otimes \mathbb{C} \} \, .$$

2.2. Generalized holomorphic (GH) map

We recall some basic facts about generalized holomorphic maps, an analogue of holomorphic maps in the case of GC manifolds. For most of the definitions, we shall rely upon [14] and [25].

Let (V, \mathcal{J}_V) be a GC linear space with +i-eigenspace L_V . Given a subspace $E \leq V \otimes \mathbb{C}$ and an element $\sigma \in \wedge^2 E^*$, consider the subspace

$$L(E,\sigma) := \{X + \xi \in E \oplus V^* \otimes \mathbb{C} \mid \xi|_E = \sigma(X)\}, \qquad (2.5)$$

of $(V \oplus V^*) \otimes \mathbb{C}$. By [14, Proposition 2.6], $L(E, \sigma)$ is a maximal isotropic subspace of $(V \oplus V^*) \otimes \mathbb{C}$ with respect to the bilinear pairing (2.1), and any maximal isotropic subspace of $(V \oplus V^*) \otimes \mathbb{C}$ is of this form. Consider the projection map

 $\rho: (V \oplus V^*) \otimes \mathbb{C} \longrightarrow V \otimes \mathbb{C}.$

Let $\rho(L_V) = E_V$ and let $E_V \cap \overline{E_V} = \Delta_V \otimes \mathbb{C}$ where $\Delta_V \leq V$ is a real subspace. Then by [14, Proposition 4.4], we have

(1) $L_V = L(E_V, \sigma)$ for some $\sigma \in \wedge^2 E_V^*$;

(2) $E_V + \overline{E_V} = V \otimes \mathbb{C}$ with a non-degenerate form $\Omega_{\Delta_V} := \operatorname{Im}(\sigma|_{\Delta_V \otimes \mathbb{C}})$ on $\Delta_V \otimes \mathbb{C}$. Since Ω_{Δ_V} is non-degenerate, following [25, Section 3], $\widetilde{P}_V := L(\Delta_V \otimes \mathbb{C}, \Omega_{\Delta_V})$ is called the associated *linear Poisson structure* of \mathcal{J}_V on $V \otimes \mathbb{C}$.

Definition 2.5. ([25]) Let $\psi : (V, \mathcal{J}_V) \longrightarrow (V', \mathcal{J}_{V'})$ be a linear map between two GC linear spaces. Then ψ is called a *generalized complex (GC) map* if

(1)
$$\psi(E_V) \subseteq E_{V'}$$
;

(2) $\psi_{\star}(\tilde{P}_V) = \tilde{P}_{V'}$ where ψ_{\star} denotes the pushforward of a Dirac structure, as in [25, Section 1], namely,

$$\psi_{\star}(\widetilde{P}_{V}) = \{\psi(Y) + \eta \in (V' \oplus V'^{*}) \otimes \mathbb{C} \mid Y + \psi^{*}(\eta) \in \widetilde{P}_{V}\}.$$

Definition 2.6. ([25]) A smooth map $\psi : (M, \mathcal{J}_M) \longrightarrow (M', \mathcal{J}_{M'})$ between two GC manifolds is called a *generalized holomorphic (GH) map* if for each $x \in M$,

$$(\psi_*)_x: T_x M \longrightarrow T_{\psi(x)} M'$$

is a GC map. If $(M', \mathcal{J}_{M'}) = (\mathbb{R}^2, \mathcal{J}_{\mathbb{R}^2})$ where $\mathcal{J}_{\mathbb{R}^2}$ is as in Example 2.3, and $(\mathbb{R}^2, J_{\mathbb{R}^2}) = \mathbb{C}$, with $J_{\mathbb{R}^2}$ being the standard complex structure on \mathbb{R}^2 , then ψ is called a *GH function*.

Remark 2.7. Given a *B*-field transformation of \mathcal{J}_V , we see that $\rho((L_V)_B) = \rho(L_V)$ where $(L_V)_B$ is as in (2.4). Since the imaginary part of σ is also preserved, the associated linear Poisson structures are the same for both GCS. This shows that the notions of GC map and GH map are insensitive to *B*-field transformations.

Let (V, \mathcal{J}_V) be a generalized complex (GC) linear space. Then \mathcal{J}_V can be written as

$$\mathcal{J}_V = \begin{pmatrix} -J_V & \beta_V \\ B_V & J_V^* \end{pmatrix}$$

where $J_V \in \text{End}(V)$, $B_V \in \text{Hom}_{\mathbb{R}}(V, V^*)$ and $\beta_V \in \text{Hom}_{\mathbb{R}}(V^*, V)$. Using $\mathcal{J}_V^* = -\mathcal{J}_V$ (cf. Definition 2.2), we get $B_V \in \wedge^2 V^*$ and $\beta_V \in \wedge^2 V$.

Lemma 2.8. Let $\psi : V \longrightarrow W$ be a GC map between two GC linear spaces. Then $\psi(E_V \cap \overline{E_V}) = E_W \cap \overline{E_W}$.

Proof. Let $w \in \Delta_W \otimes \mathbb{C} = E_W \cap \overline{E_W}$. Then $w + \Omega_{\Delta_W}(w) \in \widetilde{P}_W$. Since $\psi_{\star}(\widetilde{P}_V) = \widetilde{P}_W$, there exist $v \in \Delta_V \otimes \mathbb{C} = E_V \cap \overline{E_V}$ and $\eta \in W^* \otimes \mathbb{C}$ such that

$$w + \Omega_{\Delta_W}(w) = \psi(v) + \eta$$
.

This shows that $\psi(v) = w$ and $E_W \cap \overline{E_W} \subseteq \psi(E_V \cap \overline{E_V})$.

For the converse part, let $v \in E_V \cap \overline{E_V}$ be a non-zero element. Let $\psi(v) = w \in W \otimes \mathbb{C}$, and let $\widetilde{\Omega}_{\Delta_W} : W \otimes \mathbb{C} \longrightarrow \Delta_W^* \otimes \mathbb{C}$ be an extension of $\Omega_{\Delta_W} : \Delta_W \otimes \mathbb{C} \longrightarrow \Delta_W^* \otimes \mathbb{C}$ such that $\widetilde{\Omega}_{\Delta_W} \in \wedge^2 W^* \otimes \mathbb{C}$. Then, we have $\psi^*(\widetilde{\Omega}_{\Delta_W}(w)) \in V^* \otimes \mathbb{C}$ and

$$\Omega_{\Delta_V}^{-1}(\psi^*(\widetilde{\Omega}_{\Delta_W}(w))|_{\Delta_V \otimes \mathbb{C}}) + \psi^*(\widetilde{\Omega}_{\Delta_W}(w)) \in \widetilde{P}_V.$$
(2.6)

Denote $\Omega_{\Delta_V}^{-1}(\psi^*(\widetilde{\Omega}_{\Delta_W}(w))|_{\Delta_V\otimes\mathbb{C}}) \in \Delta_V\otimes\mathbb{C}$ by v'. Then,

$$\begin{aligned} v' &= \Omega_{\Delta_V}^{-1}(\psi^*(\widetilde{\Omega}_{\Delta_W}(w))|_{\Delta_V \otimes \mathbb{C}}) \\ \implies &\Omega_{\Delta_V}(v') = \psi^*(\widetilde{\Omega}_{\Delta_W}(w))|_{\Delta_V \otimes \mathbb{C}} \\ \implies &\Omega_{\Delta_V}(v')(v) = \psi^*(\widetilde{\Omega}_{\Delta_W}(w))(v) \\ \implies &\Omega_{\Delta_V}(v')(v) = \widetilde{\Omega}_{\Delta_W}(w)(\psi(v)) \\ \implies &\Omega_{\Delta_V}(v',v) = 0 \quad (\text{as } \psi(v) = w) \\ \implies &v = kv' \quad (\text{as } \Omega_{\Delta_V} \text{ is non-degenerate on } E_V \cap \overline{E_V} \text{ and } k \in \mathbb{C} \setminus \{0\}) \\ \implies &v = k \Omega_{\Delta_V}^{-1}(\psi^*(\widetilde{\Omega}_{\Delta_W}(w))|_{\Delta_V \otimes \mathbb{C}}). \end{aligned}$$

Note that $\psi(\Omega_{\Delta_V}^{-1}(\psi^*(\widetilde{\Omega}_{\Delta_W}(w))|_{\Delta_V \otimes \mathbb{C}}) + (\widetilde{\Omega}_{\Delta_W}(w)) \in \widetilde{P}_W$ by (2.6), and also

$$\psi(\Omega_{\Delta_V}^{-1}(\psi^*(\widetilde{\Omega}_{\Delta_W}(w))|_{\Delta_V \otimes \mathbb{C}}) = \frac{1}{k}\psi(v) = \frac{1}{k}w.$$

Thus $w \in E_W \cap \overline{E_W}$ and $\psi(E_V \cap \overline{E_V}) \subseteq E_W \cap \overline{E_W}$. This proves the lemma.

Remark 2.9. The assertion made in the statement of Lemma 2.8 is claimed in the proof of [25, Proposition 3.2]. However, the argument given there is not very explicit.

The proofs of the next two lemmas are modelled on similar arguments in [22].

Lemma 2.10. Let (V, \mathcal{J}_V) and (W, \mathcal{J}_W) are GC linear spaces with

$$\mathcal{J}_V = \begin{pmatrix} -J_V & \beta_V \\ B_V & J_V^* \end{pmatrix} \quad and \quad \mathcal{J}_W = \begin{pmatrix} -J_W & 0 \\ 0 & J_W^* \end{pmatrix}$$

where J_W is a complex structure on W. Then $\psi: V \longrightarrow W$ is a GC map if and only if

 $\psi \circ J_V = J_W \circ \psi$, $\psi \circ \beta_V = 0$.

Proof. Let dim V = 2n and let the type of \mathcal{J}_V be $k \in \mathbb{N} \cup \{0\}$. Since the definition of GC map is invariant under a *B*-transformation, we can assume without loss of generality that

 $(V, \mathcal{J}_V) = (V_1, J_1) \oplus (V_2, J_2),$

where $(V_1, J_1) = (\mathbb{R}^{2k}, J_{\mathbb{R}^{2k}}) = \mathbb{C}^k$ and $(V_2, J_2) = (\mathbb{R}^{2n-2k}, \omega_0)$. Here, $J_{\mathbb{R}^{2k}}$ and ω_0 denote the standard complex and symplectic structures on the corresponding spaces. It follows that $E_V = V_1^{0,1} \oplus (V_2 \otimes \mathbb{C})$. Since $E_V \cap \overline{E_V} = V_2 \otimes \mathbb{C}$, the Poisson bi-vector on V is

$$\widetilde{\beta}_V = \begin{cases} 0, & \text{on } V_1^* \otimes \mathbb{C} ,\\ \omega_0^{-1}, & \text{on } V_2^* \otimes \mathbb{C} . \end{cases}$$

Hence,

$$\widetilde{P}_V = L(V_2 \otimes \mathbb{C}, \omega_0) = L(V^* \otimes \mathbb{C}, \widetilde{\beta}_V).$$

Similarly, as W is a complex vector space, we have $E_W = W^{0,1}$ and so, $E_W \cap \overline{E_W} = \{0\}$. Thus, β_W , the Poisson bivector on W is 0 and we get

$$\widetilde{P}_W = W^* \otimes \mathbb{C} = L(W^* \otimes \mathbb{C}, 0)$$
.

Then, by Lemma 2.8, $\psi_{\star}(\tilde{P}_V) = \tilde{P}_W$ if and only if $\psi \circ \omega_0^{-1} = 0$. Thus, ψ is a GC map if and only if

$$\psi(V_1^{0,1} \oplus (V_2 \otimes \mathbb{C})) \subset W^{0,1}$$
 and $\psi \circ \omega_0^{-1} = 0$.

Hence, for any $v_1 \in V_1$ and $v_2 \in V_2$, we have

$$\psi((-J_1(v_1))) = (-J_W)(\psi(v_1))$$
 and $\psi(v_2) = 0$.

This implies

$$\psi \circ J_V = J_W \circ \psi$$
 and $\psi \circ \beta_V = 0$

where

$$J_V = \begin{pmatrix} J_1 & 0\\ 0 & 0 \end{pmatrix} \quad \text{and} \quad \beta_V = -\widetilde{\beta}_V = \begin{pmatrix} 0 & 0\\ 0 & -\omega_0^{-1} \end{pmatrix} \,.$$

Let ψ be any complex valued linear function on V. Considered as an element of $V^* \otimes \mathbb{C}$, ψ has two components corresponding to the decomposition $(V \oplus V^*) \otimes \mathbb{C} = L_V \oplus \overline{L_V}$, namely ψ_{L_V} and $\psi_{\overline{L_V}}$.

Lemma 2.11. A linear map $\psi : (V, \mathcal{J}_V) \longrightarrow \mathbb{C} = (\mathbb{R}^2, J_{\mathbb{R}^2})$ between two GC linear spaces, is a GC map if and only if $\psi \in (L_V \cap (V^* \otimes \mathbb{C}))$ that is, $\psi_{\overline{L_V}} = 0$.

Proof. Let \mathcal{J}_V be written as

$$\mathcal{J}_V = \begin{pmatrix} -J_V & \beta_V \\ B_V & J_V^* \end{pmatrix} \,.$$

Suppose $\psi : (V, \mathcal{J}_V) \longrightarrow (\mathbb{R}^2, J_{\mathbb{R}^2})$ is linear a GC map. Let

$$\psi_{L_V} = Y_1 + \eta_1 , \psi_{\overline{L_V}} = Y_2 + \eta_2 .$$
(2.7)

where $Y_1, Y_2 \in V \otimes \mathbb{C}$ and $\eta_1, \eta_2 \in V^* \otimes \mathbb{C}$. Then, considering ψ as an element of $V^* \otimes \mathbb{C}$, we have $Y_1 + Y_2 = 0$ and $\eta_1 + \eta_2 = \psi$. Since $\psi_{L_V} \in L_V$ and $\psi_{\overline{L_V}} \in \overline{L_V}$, we have the following equations,

$$-J_V(Y_1) + \beta_V(\eta_1) = iY_1, \quad B_V(Y_1) + J_V^*(\eta_1) = i\eta_1, -J_V(Y_2) + \beta_V(\eta_2) = -iY_2, \quad B_V(Y_2) + J_V^*(\eta_2) = -i\eta_2.$$
(2.8)

Now, by Lemma 2.10, $\psi \circ \beta_V = 0$ which implies $\beta_V(\psi) = 0$. By adding the equations in the first column in (2.8), we get $\beta_V(\psi) = i(Y_1 - Y_2)$ which implies $Y_1 = Y_2$. Since

 $Y_1+Y_2=0$, we derive $Y_1=Y_2=0$. Then, the second column in (2.8) yields $J_V^*(\eta_1)=i\eta_1$ and $J_V^*(\eta_2) = -i\eta_2$. Adding these, we obtain

$$J_V^*(\psi) = i(\eta_1 - \eta_2)$$

$$\implies \psi \circ J_V = i(\eta_1 - \eta_2)$$

$$\implies J_{\mathbb{R}^2} \circ \psi = i(\eta_1 - \eta_2) \text{ (by Lemma 2.10)}$$

$$\implies i(\eta_1 + \eta_2) = i(\eta_1 - \eta_2)$$

$$\implies \eta_2 = 0.$$

It follows that $\psi_{\overline{L_V}} = 0$.

Conversely, Suppose $\psi_{\overline{L_V}} = 0$. Then $\psi \in L_V$ and so $\mathcal{J}_V(\psi) = i\psi$. This implies that

$$\beta_V(\psi) = 0, \quad J_V^*(\psi) = i\psi,$$

$$\implies \psi \circ \beta = 0, \quad \psi \circ J_V = J_{\mathbb{R}^2} \circ \psi$$

Thus, by Lemma 2.10, ψ is a GC map.

Let (M, \mathcal{J}_M) be a GC manifold with +i-eigenbundle L_M so that we have,

$$(TM \oplus T^*M) \otimes \mathbb{C} = L_M \oplus \overline{L_M}.$$

Let d be the exterior derivative on M.

Lemma 2.12. Given an open set $U \subseteq M$, a smooth map $\psi : (U, \mathcal{J}_U) \longrightarrow \mathbb{C} = (\mathbb{R}^2, J_{\mathbb{R}^2})$ is a GH function if and only if for each $x \in U$, $d\psi_x \in (L_M \cap (T^*M \otimes \mathbb{C}))_x$.

Proof. Follows from Lemma 2.11 and Definition 2.6.

Definition 2.13. Let \mathcal{O}_M denote the sheaf of \mathbb{C} -valued GH functions on M.

By Lemma 2.12, \mathcal{O}_M is a subsheaf of the sheaf of smooth \mathbb{C} -valued functions on M. To begin with, we consider some simple examples of \mathcal{O}_M .

(1) When (M, J_M) is a complex manifold with J_M as its complex structure. Then the induced natural GCS is, as given in Example 2.3,

$$\mathcal{J}_M := \begin{pmatrix} -J_M & 0\\ 0 & J_M^* \end{pmatrix}$$

with its +i-eigenbundle

$$L_M = T^{0,1}M \oplus (T^{1,0}M)^*$$
.

By Lemma 2.12, we can see that, given any GH map ψ , $d\psi \in \Omega^{1,0}(M)$ that is, ψ is a holomorphic function. So \mathcal{O}_M will be the sheaf of holomorphic functions on M.

(2) When (M, ω) is a symplectic manifold with a symplectic structure ω . The induced GCS, as given in Example 2.4,

$$\mathcal{J}_M := \begin{pmatrix} 0 & -\omega^{-1} \\ \omega & 0 \end{pmatrix}$$

with its +i-eigenbundle

$$L_M = \{ X - i\omega(X) \, | \, X \in TM \otimes \mathbb{C} \}$$

which is naturally identified with $TM \otimes \mathbb{C}$. So for any GH map ψ , $d\psi = 0$ which implies ψ is constant. Hence \mathcal{O}_M is a constant sheaf.

Definition 2.14. (cf. [22]) A diffeomorphism $\phi : (M, \mathcal{J}_M) \longrightarrow (N, \mathcal{J}_N)$ between two GC manifolds is called a *generalized holomorphic (GH) homeomorphism* if

$$\begin{pmatrix} \phi_* & 0\\ 0 & (\phi^{-1})^* \end{pmatrix} \circ \mathcal{J}_M = \mathcal{J}_N \circ \begin{pmatrix} \phi_* & 0\\ 0 & (\phi^{-1})^* \end{pmatrix}.$$
(2.9)

When N = M, ϕ is called GH automorphism.

Remark 2.15. Note that a GH homeomorphism ϕ and its inverse ϕ^{-1} are both GH maps. This can be observed as follows. Let L_M, L_N denote the +i-eigen bundles of $\mathcal{J}_M, \mathcal{J}_N$, respectively. For every point p in M, consider the subset of $(T_{\phi(p)}N \oplus T^*_{\phi(p)}N) \otimes \mathbb{C}$

$$\phi_{\star}(L_M \mid_p) := \{ \phi_{\star}(X) + \eta \mid X + \phi^{\star} \eta \in L_M \mid_p \}.$$

Then, for any $X \in T_p M \otimes \mathbb{C}$ and $\eta \in T^*_{\phi(p)} N \otimes \mathbb{C}$

$$J_N(\phi_*(X) + \eta) = \mathcal{J}_N\left(\begin{pmatrix}\phi_* & 0\\ 0 & (\phi^{-1})^*\end{pmatrix}(X + \phi^*\eta)\right).$$

By (2.9), we get $Y + \xi \in \phi_{\star}(L_M)$ if and only $Y + \xi \in L_N$, that is $\phi_{\star}(L_M) = L_N$, and using [25, Corollary 3.3], we conclude that both ϕ and ϕ^{-1} are GH maps. But the converse is not true always. A GH map which is a diffeomorphism may not always be a GH homeomorphism. The reason is that a GH map is defined up to a *B*-transformation whereas a GH homeomorphism between two GC manifolds shows that their GC structures are the same.

Definition 2.16. Let $\rho : (TM \oplus T^*M) \otimes \mathbb{C} \longrightarrow TM \otimes \mathbb{C}$ denote the natural projection. We denote by E_M the image of L_M under ρ . Let $\Delta_M \otimes \mathbb{C} := E_M \bigcap \overline{E_M}$.

For each $x \in M$, type of \mathcal{J}_M at x is defined as

$$\operatorname{Type}(x) := \operatorname{Codim}_{\mathbb{C}}((E_M)_x) = \frac{1}{2}\operatorname{Codim}_{\mathbb{R}}((\Delta_M)_x).$$

x is called a regular point of M if Type(x) is constant in a neighborhood of x and M is called a regular GC manifold if each point of M is a regular point.

we have the generalized Darboux theorem around any regular point.

Theorem 2.17. ([15, Theorem 4.3]) For a regular point $x \in (M, \mathcal{J}_M)$ of Type(x) = k, there exists an open neighborhood $U_x \subset M$ of x such that, after a *B*-transformation, U_x is GH homeomorphic to $U_1 \times U_2$, where $U_1 \subset (\mathbb{R}^{2n-2k}, \omega_0), U_2 \subset \mathbb{C}^k$ are open subsets with ω_0 being the standard symplectic structure. In a simpler terms, Theorem 2.17 implies that, for some real closed form 2-form $B_{\phi} \in \Omega^2(U_1 \times U_2)$, there exists a GH homeomorphism

$$\phi: (U_x, \mathcal{J}_{U_x}) \longrightarrow (U_1 \times U_2, (\mathcal{J}_{U_1 \times U_2})_{B_\phi})$$

where $(\mathcal{J}_{U_1 \times U_2})_{B_{\phi}}$ is the *B*-transformation, as in (2.3), of the product GCS, denoted by $\mathcal{J}_{U_1 \times U_2}$. Let $p = (p_1, \ldots, p_{2n-2k})$ and $z = (z_1, \ldots, z_k)$ represent coordinate systems for \mathbb{R}^{2n-2k} and \mathbb{C}^k , respectively, and consider the corresponding local coordinates around x

$$(U_x, \phi, p, z) := (U_x, \phi; p_1, \dots, p_{2n-2k}, z_1, \dots, z_k).$$
(2.10)

We note that the subspaces $(E_M)_x$ and $(\overline{E_M})_x$ admit the following description,

$$(E_M)_x = \operatorname{Span} \left\{ \partial_{p_i} \mid_x, \partial_{\overline{z_j}} \mid_x : 1 \le i \le 2n - 2k, 1 \le j \le k \right\},$$

$$(\overline{E_M})_x = \operatorname{Span} \left\{ \partial_{p_i} \mid_x, \partial_{z_j} \mid_x : 1 \le i \le 2n - 2k, 1 \le j \le k \right\}.$$

$$(2.11)$$

Using Theorem 2.17 in the case of a regular GC manifold, we can obtain a nice description of coordinate transformations, as given in the following corollary.

Corollary 2.18. ([22, Proposition 2.7]) Let (M, \mathcal{J}_M) be a regular GC manifold of type k. Let's assume that (U, ϕ, p, z) and (U', ϕ', p', z') are two local coordinate systems, as in (2.10), with $U \cap U' \neq \emptyset$. Then, the coordinate transformation satisfies the following condition

$$\frac{\partial z'_i}{\partial \overline{z_j}} = \frac{\partial z'_i}{\partial p_l} = 0 \quad \text{for all} \quad i, j \in \{1, \dots, k\}, l \in \{1, \dots, 2n - 2k\}$$

Furthermore, the local coordinates in (2.10) provide a requisite and complete condition for GH functions on a regular GC manifold, as demonstrated below.

Proposition 2.19. ([22, Example 2.8]) Let (M, \mathcal{J}_M) be a regular type k GC manifold. Then, $f: M \longrightarrow \mathbb{C}$ is a GH function if and only if at every point on M, expressed in terms of local coordinates, as shown in (2.10), f satisfies the following

$$\frac{\partial f}{\partial \overline{z_j}} = \frac{\partial f}{\partial p_l} = 0 \quad \text{for all} \quad i, j \in \{1, \dots, k\}, l \in \{1, \dots, 2n - 2k\}.$$

This implies that for a regular GC manifold of type k, the sheaf \mathcal{O}_M is locally given by the ring of convergent power series in the coordinates $z = (z_1, \ldots, z_k)$ in (2.10).

3. Strong Generalized Holomorphic Fiber bundle

Let (M, \mathcal{J}_M) be a generalized complex (GC) manifold. Then \mathcal{J}_M can be written as

$$\mathcal{J}_M = \begin{pmatrix} -J_M & \beta_M \\ B_M & J_M^* \end{pmatrix} \tag{3.1}$$

where $J_M \in \text{End}(TM)$, $B_M \in \Omega^2(M)$ and $\beta_M \in \mathfrak{X}^2(M)$. Let $\text{Diff}_{\mathcal{J}_M}(M)$ denote the subgroup of Diff(M) defined by

$$\operatorname{Diff}_{\mathcal{J}_M}(M) := \{ \phi \in \operatorname{Diff}(M) \mid \phi \text{ is a GH automorphism of } (M, \mathcal{J}_M) \}.$$
(3.2)

Definition 3.1. Let G be a connected Lie group. A smooth fiber bundle $F \hookrightarrow E \xrightarrow{\pi} M$ over a GC manifold (M, \mathcal{J}_M) with a typical fiber (F, \mathcal{J}_F) and structure group G is called an *strong generalized holomorphic (SGH) fiber bundle* if

- (1) E is a GC manifold,
- (2) there is an open cover $\{U_{\alpha}\}$ of M and a family of local trivializations $\{\phi_{\alpha}\}$ of E

$$\{\phi_{\alpha}: \pi^{-1}(U_{\alpha}) \longrightarrow U_{\alpha} \times F\}$$

such that every ϕ_{α} is a GH homeomorphism when $U_{\alpha} \times F$ is endowed with the standard product GC structure.

In addition, if F is a vector space and G is a subgroup of GL(F), then we say that E is an SGH vector bundle over M.

The following theorem is a generalization of [22, Proposition 3.2].

Theorem 3.2. Let E be a fiber bundle over (M, \mathcal{J}_M) with typical fiber (F, \mathcal{J}_F) and structure group G. Let $\{U_{\alpha}, \phi_{\alpha}\}$ be a family of local trivializations with transition functions $\phi_{\alpha\beta}$ as follows,

$$\{\phi_{\alpha}: \pi^{-1}(U_{\alpha}) \longrightarrow U_{\alpha} \times F\}, \ \phi_{\alpha\beta}: U_{\alpha\beta} = U_{\alpha} \cap U_{\beta} \longrightarrow G,$$

where $\phi_{\alpha\beta}(x) = \phi_{\alpha}|_{\pi^{-1}(x)} \circ \phi_{\beta}^{-1}(x, \cdot)$ for all $x \in U_{\alpha\beta}$. Then, E is SGH fiber bundle over M with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ if and only if

- (1) $\phi_{\alpha\beta}(m) \in \text{Diff}_{\mathcal{J}_F}(F)$ for all $m \in U_{\alpha\beta}$,
- (2) For each $(m, f) \in M \times F$, the following equations hold:

$$\begin{aligned} (\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} \circ J_{U_{\alpha\beta}} &= J_F \circ (\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} \,, \\ (\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} \circ \beta_{U_{\alpha\beta}} &= 0 \,, \\ B_F \circ (\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} &= 0 \,, \end{aligned}$$

for all $(m, f) \in M \times F$, where $J_{U_{\alpha\beta}}, J_F, \beta_{U_{\alpha\beta}}, B_F$ are as in equation (3.1), and the map $\rho_f : G \longrightarrow F$ is defined as $\rho_f(g) := g \cdot f$.

Proof. Consider the map

$$\psi_{\alpha\beta} = \phi_{\alpha} \circ \phi_{\beta}^{-1} : U_{\alpha\beta} \times F \longrightarrow U_{\alpha\beta} \times F .$$
(3.3)

Note that $\psi_{\alpha\beta}(m, f) = (m, \phi_{\alpha\beta}(m) \cdot f)$ for all $(m, f) \in U_{\alpha\beta} \times F$.

First, we claim that E is an SGH fiber bundle if and only if $\psi_{\alpha\beta}$ is a GH automorphism for any fixed α, β . Indeed, if $\psi_{\alpha\beta}$ is a GH automorphism, then

$$\begin{pmatrix} (\psi_{\alpha\beta})_* & 0\\ 0 & (\psi_{\beta\alpha})^* \end{pmatrix} \circ \mathcal{J}_{U_{\alpha\beta} \times F} = \mathcal{J}_{U_{\alpha\beta} \times F} \circ \begin{pmatrix} (\psi_{\alpha\beta})_* & 0\\ 0 & (\psi_{\beta\alpha})^* \end{pmatrix}, \quad (3.4)$$

where $\mathcal{J}_{U_{\alpha\beta}\times F} = (J_{ij})_{2\times 2}$ is the product GC structure on $U_{\alpha\beta} \times F$. Then

$$\begin{pmatrix} (\phi_{\alpha}^{-1})_* & 0\\ 0 & (\phi_{\alpha})^* \end{pmatrix} \circ (J_{ij})_{2 \times 2} \circ \begin{pmatrix} (\phi_{\alpha})_* & 0\\ 0 & (\phi_{\alpha}^{-1})^* \end{pmatrix}$$
(3.5)

is an endomorphism of $T\pi^{-1}(U_{\alpha}) \oplus T^*\pi^{-1}(U_{\alpha})$ that produces the GC structure on $\pi^{-1}(U_{\alpha})$. By equation (3.4) this structure is independent of the choice of ϕ_{α} . Hence, we obtain a GC structure on E such that ϕ_{α} becomes GH homeomorphism. The converse is obvious.

Now, it is enough to show that $\psi_{\alpha\beta}$ is a GH automorphism if and only if (1) and (2) are satisfied.

The product GC structure on $U_{\alpha\beta} \times F$ can be expressed as

$$J_{11} = \begin{pmatrix} -J_{U_{\alpha\beta}} & 0\\ 0 & -J_F \end{pmatrix}, \ J_{21} = \begin{pmatrix} B_{U_{\alpha\beta}} & 0\\ 0 & B_F \end{pmatrix},$$
$$J_{12} = \begin{pmatrix} \beta_{U_{\alpha\beta}} & 0\\ 0 & \beta_F \end{pmatrix}, \ J_{22} = \begin{pmatrix} J_{U_{\alpha\beta}}^* & 0\\ 0 & J_F^* \end{pmatrix}.$$

Upon simplification, the expression for equation (3.4), at $(m, f) \in U_{\alpha\beta} \times F$, can be represented as:

$$(\psi_{\alpha\beta})_{*(m,f)} \circ J_{11} = J_{11} \circ (\psi_{\alpha\beta})_{*(m,f)}, \qquad (3.6)$$

$$(\psi_{\alpha\beta})_{*(m,f)} \circ J_{12} = J_{12} \circ (\psi_{\beta\alpha})^{*}_{(m,f)}, \qquad (3.7)$$

$$(\psi_{\beta\alpha})^*_{(m,f)} \circ J_{21} = J_{21} \circ (\psi_{\alpha\beta})_{*(m,f)}, \qquad (3.8)$$

$$(\psi_{\beta\alpha})^*_{(m,f)} \circ J_{22} = J_{22} \circ (\psi_{\beta\alpha})^*_{(m,f)} .$$
(3.9)

 $(\psi_{\beta\alpha})^*_{(m,f)} \circ J_{22} = J_{22} \circ (\psi_{\beta\alpha})^*_{(m,f)}.$ Since $\psi_{\alpha\beta}(m,f) = (m, \phi_{\alpha\beta}(m) \cdot f)$ where $\phi_{\alpha\beta}(m) \in G$, the map

$$(\psi_{\alpha\beta})_{*(m,f)}: T_m U_{\alpha\beta} \oplus T_f F \longrightarrow T_m U_{\alpha\beta} \oplus T_{\phi_{\alpha\beta}(m) \cdot f} F$$

can be expressed as

$$(\psi_{\alpha\beta})_{*(m,f)} = \begin{pmatrix} Id_{U_{\alpha\beta}} & 0\\ (\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} & (\phi_{\alpha\beta}(m))_* \end{pmatrix}, \qquad (3.10)$$

and the map

$$(\psi_{\beta\alpha})^*_{(m,f)}: T^*_m U_{\alpha\beta} \oplus T^*_f F \longrightarrow T^*_m U_{\alpha\beta} \oplus T^*_{\phi_{\alpha\beta}(m) \cdot f} F$$

can be expressed as

$$(\psi_{\beta\alpha})^*_{(m,f)} = \begin{pmatrix} Id_{U_{\alpha\beta}} & (\phi_{\beta\alpha})^*_m \circ \rho^*_{\phi_{\alpha\beta}(m) \cdot f} \\ 0 & (\phi_{\beta\alpha}(m))^* \end{pmatrix}.$$
(3.11)

From equations (3.6) and (3.10), we have

$$(\phi_{\alpha\beta}(m))_* \circ (-J_F) = (-J_F) \circ (\phi_{\alpha\beta}(m))_*$$
(3.12)

and

$$(\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} \circ (-J_{U_{\alpha\beta}}) = (-J_F) \circ (\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} \,. \tag{3.13}$$

Using equations (3.7), (3.10) and (3.11), we get

$$(\phi_{\alpha\beta}(m))_* \circ \beta_F = \beta_F \circ (\phi_{\beta\alpha}(m))^*, \qquad (3.14)$$

$$(\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} \circ \beta_{U_{\alpha\beta}} = 0, \qquad (3.15)$$

and

$$\beta_{U_{\alpha\beta}} \circ (\phi_{\beta\alpha})^*_m \circ \rho^*_{\phi_{\alpha\beta}(m) \cdot f} = 0.$$
(3.16)

From equations (3.8), (3.10) and (3.11), we have

$$(\phi_{\beta\alpha}(m))^* \circ B_F = B_F \circ (\phi_{\alpha\beta}(m))_*, \qquad (3.17)$$

$$(\phi_{\beta\alpha})_m^* \circ \rho_{\phi_{\alpha\beta}(m) \cdot f}^* \circ B_F = 0, \qquad (3.18)$$

and

$$B_F \circ (\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} = 0.$$
(3.19)

From equations (3.9) and (3.11), we have

$$(\phi_{\beta\alpha}(m))^* \circ J_F^* = J_F^* \circ (\phi_{\beta\alpha}(m))^*$$
(3.20)

and

$$(\phi_{\beta\alpha})^*_m \circ \rho^*_{\phi_{\alpha\beta}(m) \cdot f} \circ J^*_F = J^*_{U_{\alpha\beta}} \circ (\phi_{\beta\alpha})^*_m \circ \rho^*_{\phi_{\alpha\beta}(m) \cdot f}.$$
(3.21)

Now, we can see that equations (3.12), (3.14), (3.17) and (3.20) hold if and only if

$$\begin{pmatrix} (\phi_{\alpha\beta}(m))_* & 0\\ 0 & (\phi_{\beta\alpha}(m))^* \end{pmatrix} \circ \mathcal{J}_F = \mathcal{J}_F \circ \begin{pmatrix} (\phi_{\alpha\beta}(m))_* & 0\\ 0 & (\phi_{\beta\alpha}(m))^* \end{pmatrix}$$
(3.22)

where $\mathcal{J}_F = \begin{pmatrix} -J_F & \beta_F \\ B_F & J_F^* \end{pmatrix}$ as in (3.1). Therefore, equations (3.12), (3.14), (3.17) and (3.20) hold if and only if $\phi_{\beta\alpha}(m) \in \text{Diff}_{\mathcal{J}_F}(F)$. Note that, by skew-symmetry, $\beta_{U_{\alpha\beta}}^* = -\beta_{U_{\alpha\beta}}$ and $B_F^* = -B_F$. Since (m, f) is arbitrary, considering duals, we observe that

- equation (3.15) holds if and only if equation (3.16) holds,
- equation (3.19) holds if and only if equation (3.18) holds,
- equations (3.13) and (3.21) are equivalent to each other.

Therefore, $\psi_{\alpha\beta}$ is a GH automorphism if and only if equations (3.13), (3.15), (3.19) and (3.22) hold. Hence, $\psi_{\alpha\beta}$ is a GH automorphism if and only if (1) and (2) are satisfied as desired.

Definition 3.3. Let E be an SGH fiber bundle over a GC manifold (M, \mathcal{J}_M) and $U \subseteq M$ be an open set. A smooth section $s : U \longrightarrow E$ is called a GH section if s is a GH map from $(U, \mathcal{J}_M|_U)$ to (E, \mathcal{J}_E) .

Definition 3.4. Given any two SGH fiber bundles E and E' over M, a smooth map $\phi: E \longrightarrow E'$ is called an SGH bundle homomorphism if

(1) ϕ is a bundle homomorphism between E and E' as smooth fiber bundles.

(2) ϕ is a GH map.

If, in addition, ϕ is a GH homeomorphism, then $\phi : E \longrightarrow E'$ is called SGH bundle isomorphism.

Example 3.5. Let E be an SGH fiber bundle over a GC manifold (M, \mathcal{J}_M) . Let a symplectic manifold (F, ω) be its typical fiber. The GC structure on F can be expressed as

$$\mathcal{J}_F = \begin{pmatrix} 0 & -\omega^{-1} \\ \omega & 0 \end{pmatrix} \,.$$

Note that $J_F = J_F^* = 0$ and $B_F = -\beta_F^{-1} = \omega$. Since ω is non-degenerate and $f \in F$ is arbitrary, for each $m \in M$, equation (3.19) holds if and only if $(\phi_{\alpha\beta})_{*m} = 0$, i.e., $\phi_{\alpha\beta}$ is a locally constant map on $U_{\alpha\beta}$. From equation (3.17), for $X, Y \in TM$, we have

$$\omega = (\phi_{\alpha\beta}(m))^* \circ \omega \circ (\phi_{\alpha\beta}(m))_*$$

$$\Longrightarrow \omega(X) = (\phi_{\alpha\beta}(m))^* (\omega((\phi_{\alpha\beta}(m))_*(X)))$$

$$\Longrightarrow \omega(X, Y) = \omega((\phi_{\alpha\beta}(m))_*(X), (\phi_{\alpha\beta}(m))_*(Y))$$

$$\Longrightarrow \omega(X, Y) = (\phi_{\alpha\beta}(m))^* \omega(X, Y).$$

Lemma 3.6. Any SGH fiber bundle E over a GC manifold M with a symplectic fiber (F, ω) is a smooth symplectic fiber bundle with a flat connection.

Example 3.7. Let *E* be an SGH fiber bundle over a symplectic manifold (M, ω) with a typical fiber (F, \mathcal{J}_F) . The GC structure on the base is given by

$$\mathcal{J}_M = \begin{pmatrix} 0 & -\omega^{-1} \\ \omega & 0 \end{pmatrix}$$
.

Note that $J_M = J_M^* = 0$ and $B_M = -\beta^{-1} = \omega$. Since ω is nondegenarate, by equation (3.15), for any $(m, f) \in U_{\alpha\beta} \times F$, $(\rho_f)_* \circ (\phi_{\alpha\beta})_{*m} = 0$. Thus, $(\phi_{\alpha\beta})_{*m} = 0$, i.e., $\phi_{\alpha\beta}$ is locally constant on $U_{\alpha\beta}$. So, equations (3.13) and (3.19) are also satisfied. Hence, we have the following.

Lemma 3.8. E be a smooth fiber bundle over a symplectic manifold (M, ω) with a typical fiber (F, \mathcal{J}_F) . Then, E is SGH fiber bundle over M with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ if and only if

- (1) $\phi_{\alpha\beta}(m) \in \operatorname{Diff}_{\mathcal{J}_F}(F)$ for all $m \in U_{\alpha\beta}$,
- (2) $\phi_{\alpha\beta}$ is constant on $U_{\alpha\beta}$, that is, E admits a flat connection.

Proposition 3.9. Let (M, \mathcal{J}_M) be a GC manifold and (N, J_N) be a complex manifold with a complex structure J_N . Then, for any smooth map $\psi : M \longrightarrow N$, the following are equivalent.

- (1) ψ is a GH map.
- (2) For any open set $U \subset M$, $\psi: U \longrightarrow N$ is a GH map.

(3) $\psi_* \circ J_M = J_N \circ \psi_*$, $\psi_* \circ \beta_M = 0$.

Here \mathcal{J}_M is as in (3.1) and N is considered as a GC manifold with the natural GC structure induced by J_N .

Proof. Follows from Lemma 2.10.

Example 3.10. Let E be an SGH fiber bundle over a GC manifold (M, \mathcal{J}_M) with typical fiber a complex manifold (F, J_F) where J_F is a complex structure on F. Then the naturally induced GC structure on F can be written as

$$\mathcal{J}_F = \begin{pmatrix} -J_F & 0 \\ 0 & J_F^* \end{pmatrix} \,.$$

We can see that $B_F = \beta_F = 0$ and also by equation (3.22), for any $m \in U_{\alpha\beta}$, $\phi_{\alpha\beta}(m)$ is a biholomorphic automorphism. By Proposition 3.9 and equation (3.15), for any $f \in F$, we can show that $\rho_f \circ \phi_{\alpha\beta}$ is a GH map. Thus we have the following result.

Lemma 3.11. Let E be a smooth fiber bundle over a GC manifold (M, \mathcal{J}_M) with typical fiber a complex manifold (F, J_F) . Let $\{U_{\alpha}, \phi_{\alpha}\}$ be a family of trivial localization. Then E is an SGH fiber bundle over M with local trivialization $\{U_{\alpha}, \phi_{\alpha}\}$ if and only if

- (1) for each $m \in U_{\alpha\beta}$, $\phi_{\alpha\beta}(m)$ is a biholomorphic map,
- (2) for any $f \in F$, $\rho_f \circ \phi_{\alpha\beta}$ is a GH map.

Remark 3.12. Note that when E denotes a vector bundle over a GC manifold M, using Lemma 3.11, we can see that E is an SGH vector bundle if and only if it is a GH vector bundle in the sense described by Lang et al. ([22, Definition 3.1]).

Example 3.13. Let M be a GC manifold and \tilde{M} be a covering space. Let $K \leq \pi_1(M)$ be a subgroup corresponding to \tilde{M} such that $\tilde{M}/K \cong M$. Note that $K \hookrightarrow \tilde{M} \xrightarrow{\pi} M$ is a principal K-bundle where π is the covering map. Since π is a local diffeomorphism, M induces a GC structure (of the same type) on \tilde{M} such that π becomes a GC map. Let $\rho: K \longrightarrow GL_l(\mathbb{C})$ be a representation. Define

$$\tilde{M} \times_{\rho} \mathbb{C}^l := \tilde{M} \times \mathbb{C}^l / \sim,$$

where $(m, z) \sim (n, w)$ if and only if $n = m \cdot g^{-1}$ and $w = \rho(g) \cdot z$ for some $g \in K$. Since K is discrete, the transition maps of the associated vector bundle $\tilde{M} \times_{\rho} \mathbb{C}^{l} \longrightarrow M$ are locally constant. Hence, by Lemma 3.11, $\tilde{M} \times_{\rho} \mathbb{C}^{l} \longrightarrow M$ is a (flat) SGH vector bundle over M.

Example 3.14. Let M_1 be a complex manifold and V be a holomorphic vector bundle over M_1 . Let M_2 be a symplectic manifold and V_2 be a flat vector bundle over M_2 . Then $\bigotimes_i \operatorname{Pr}_i^*(V_i) \longrightarrow M_1 \times M_2$ is an SGH vector bundle where $\operatorname{Pr}_i : M_1 \times M_2 \longrightarrow M_i$ is the natural projection map onto *i*-th component. Here $M_1 \times M_2$ is considered with the product GCS.

4. SGH principal bundles, SGH vector bundles, and locally free sheaves

4.1. SGH principal bundles and SGH vector bundles

Let G be a real connected Lie group with a GC structure \mathcal{J}_G . Let $G \hookrightarrow P \xrightarrow{\pi} M$ be a smooth principal G-bundle over a GC manifold (M, \mathcal{J}_M) . Let $\{U_\alpha, \phi_\alpha\}$ be a family of local trivializations

$$\phi_{\alpha}: \pi^{-1}(U_{\alpha}) \longrightarrow U_{\alpha} \times G \,, \tag{4.1}$$

with transition functions

$$\phi_{\alpha\beta}: U_{\alpha\beta} = U_{\alpha} \cap U_{\beta} \longrightarrow G , \qquad (4.2)$$

where $\phi_{\alpha\beta}(x) = \phi_{\alpha}|_{\pi^{-1}(x)} \circ \phi_{\beta}^{-1}(x, \cdot)$ for all $x \in U_{\alpha\beta}$.

Definition 4.1. P is called an SGH principal G-bundle over (M, \mathcal{J}_M) if

- (1) P is a GC manifold.
- (2) There exist local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ such that every ϕ_{α} is a GH homeomorphism when $U_{\alpha} \times G$ is endowed with the standard product GC structure.

As in (3.1), \mathcal{J}_M and \mathcal{J}_G can be written in the following form

$$\mathcal{J}_M = \begin{pmatrix} -J_M & \beta_M \\ B_M & J_M^* \end{pmatrix}$$
 and $\mathcal{J}_G = \begin{pmatrix} -J_G & \beta_G \\ B_G & J_G^* \end{pmatrix}$, respectively

Remark 4.2. Note that in the definition of an SGH principal G-bundle, we do not require that the group operations on G be GH maps, or that the left or right translations by elements of G be GH homeomorphisms. However, if we assume that G is a complex Lie group then these conditions hold.

Proposition 4.3. The following are equivalent.

- (1) *P* is an SGH principal *G*-bundle over (M, \mathcal{J}_M) with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ and transition functions $\{\phi_{\alpha\beta}\}$.
- (2) For all nonempty $U_{\alpha\beta} \subseteq M$ and $(m, f) \in U_{\alpha\beta} \times G$, the map

 $\psi_{\alpha\beta}: U_{\alpha\beta} \times G \longrightarrow U_{\alpha\beta} \times G \quad defined \ as \quad \psi_{\alpha\beta}(m, f) = (m, \phi_{\alpha\beta}(m) \cdot f)$

is a GH automorphism of $U_{\alpha\beta} \times G$.

- (3) The transition functions satisfy the following: For all $m \in U_{\alpha\beta}$,
 - (a) $\phi_{\alpha\beta}(m) \in \operatorname{Diff}_{\mathcal{J}_G}(G)$
 - (b) $(\phi_{\alpha\beta})_{*m} \circ J_{U_{\alpha\beta}} = J_F \circ (\phi_{\alpha\beta})_{*m}$,
 - (c) $(\phi_{\alpha\beta})_{*m} \circ \beta_{U_{\alpha\beta}} = 0$,
 - (d) $B_G \circ (\phi_{\alpha\beta})_{*m} = 0$.

Proof. Follows from Theorem 3.2.

Proposition 4.4. Let G be a connected complex Lie group. Then, the following are equivalent.

- (1) *P* is an SGH principal *G*-bundle over (M, \mathcal{J}_M) with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ and transition functions $\{\phi_{\alpha\beta}\}$.
- (2) For all nonempty $U_{\alpha\beta} \subseteq M$ and $(m, f) \in U_{\alpha\beta} \times G$, the map $\psi_{\alpha\beta} : U_{\alpha\beta} \times G \longrightarrow U_{\alpha\beta} \times G$ defined as $\psi_{\alpha\beta}(m, f) = (m, \phi_{\alpha\beta}(m) \cdot f)$ is a GH automorphism of $U_{\alpha\beta} \times G$.
- (3) The transition maps φ_{αβ} satisfy the following:
 (a) φ_{αβ}(m) is a biholomorphic map on G ∀ m ∈ U_{αβ},
 - (b) each $\phi_{\alpha\beta}$ is a GH map.

Proof. Follows from Proposition 4.3 and Lemma 3.11.

Let M be a GC manifold and let E be an SGH vector bundle of real rank 2l over M with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$. Then, by Theorem 3.2 and [22, Proposition 3.2], we have

(1) $\phi_{\alpha\beta}(m) \in GL_l(\mathbb{C})$, i.e., E is a complex vector bundle of of complex rank l,

(2) each entry $B_{\lambda\gamma}: U_{\alpha\beta} \longrightarrow \mathbb{C}$ of $\phi_{\alpha\beta} = (B_{\lambda\gamma})_{l \times l}$ is a GH function, where $\phi_{\alpha\beta}: U_{\alpha\beta} \longrightarrow GL_{2l}(\mathbb{R})$ is the transition map as in Theorem 3.2.

Following the standard associated principal bundle construction (cf. [27, Chapter 3]), we construct the principal bundle P_E associated to E as follows: Consider the disjoint union $\bigsqcup U_{\alpha} \times GL_l(\mathbb{C})$ where $U_{\alpha} \subset M$ varies over a trivializing open cover of E. Define an equivalence relation on this set by declaring elements $(b, h) \in U_{\alpha} \times GL_l(\mathbb{C})$ and $(a, g) \in U_{\beta} \times GL_l(\mathbb{C})$ to be equivalent if and only if a = b and $g = \phi_{\alpha\beta}(b)h$,

 $(b,h) \sim (a,g) \iff a = b \text{ and } g = \phi_{\alpha\beta}(b)h.$

Now define

$$P_E := \bigsqcup_{\alpha} U_{\alpha} \times GL_l(\mathbb{C}) \Big/ \sim .$$
(4.3)

For each $m \in U_{\alpha\beta}$,

$$\phi_{\alpha\beta}(m) \circ J_{\mathbb{R}^{2l}} = J_{\mathbb{R}^{2l}} \circ \phi_{\alpha\beta}(m) \,,$$

where $J_{\mathbb{R}^{2l}}$ denotes the natural complex structure on \mathbb{R}^{2l} , which implies $\phi_{\alpha\beta}(m)$ is biholomorphic. Considering $GL_l(\mathbb{C}) \subset GL_{2l}(\mathbb{R})$, note that the transition map $\phi_{\alpha\beta} : U_{\alpha\beta} \longrightarrow GL_l(\mathbb{C})$ is a GH map if and only if each entry

$$B_{\lambda\gamma}: U_{\alpha\beta} \longrightarrow \mathbb{C}$$

of $\phi_{\alpha\beta} = (B_{\lambda\gamma})_{l\times l}$ is a GH function. Hence, by Proposition 4.4, P_E is an SGH principal $GL_l(\mathbb{C})$ -bundle.

Given an SGH principal $GL_l(\mathbb{C})$ -bundle $\pi : P \longrightarrow M$ with local trivializations $\{U_\alpha, \phi_\alpha\}$, the associated vector bundle E_P is constructed as follows: Consider the right action of $GL_l(\mathbb{C})$ on $P \times \mathbb{C}^l$ defined by

$$(p, f) \cdot g = (p \cdot g, g^{-1}(f)) \ \forall \ p \in P, f \in \mathbb{C}^l \text{ and } g \in GL_l(\mathbb{C})$$

Define

$$E_P := P \times_{GL_l(\mathbb{C})} \mathbb{C}^l \,, \tag{4.4}$$

as the identification space of that right action. Denote by [(p, f)] the equivalence class or orbit of $(p, f) \in P \times \mathbb{C}^{\triangleleft}$ under the above action. Then, the map

 $\pi_P: E_P \longrightarrow M$

defined by $\pi_P([p, f]) = \pi(p)$ gives the desired the vector bundle structure on E_P . Note that the transition map $\phi_{\alpha\beta}$ of E_P , as in Theorem 3.2, is a GH map by Proposition 4.4. Also, $\phi_{\alpha\beta} : U_{\alpha\beta} \longrightarrow GL_l(\mathbb{C})$ is a GH map if and only if each entry

$$B_{\lambda\gamma}: U_{\alpha\beta} \longrightarrow \mathbb{C}$$

of $\phi_{\alpha\beta} = (B_{\lambda\gamma})_{l\times l}$ is a GH function. Thus, by [22, Proposition 3.2], E_P is a GH vector bundle over M. The result below now follows using standard arguments.

Proposition 4.5. Let (M, \mathcal{J}_M) be a GC manifold and $l \in \mathbb{N}$. Consider the following two sets

$\mathcal{E}_l := Set \text{ of all isomorphism classes of } SGH \text{ vector bundles of real rank } 2l \text{ over } M$,

and

$$\mathscr{P}_{GL_l(\mathbb{C})} := Set \text{ of all isomorphism classes of SGH principal}$$

 $GL_l(\mathbb{C})$ -bundles over M .

If P_E and E_P are as in the equations (4.3) and (4.4) respectively, then the map

$$\Phi: \mathscr{E}_l \longrightarrow \mathscr{P}_{GL_l(\mathbb{C})} \tag{4.5}$$

defined by $\Phi([E]) = [P_E]$ gives a bijective map between two sets with the inverse map defined as $\Phi^{-1}([P]) = [E_P]$ where [E] and [P] denotes the SGH bundle isomorphism classes of E and P, respectively.

4.2. SGH vector bundles and locally free sheaves of finite rank

Let M be a GC manifold. Let E be an SGH vector bundle of real rank 2l over M. Consider the sheaf **E** of GH sections of E over M, that is, for any open set $U \subseteq M$,

 $\Gamma(U, \mathbf{E}) := \{ s \in C^{\infty}(U, E) \mid s \text{ is a GH section of } E \text{ over } U \}.$

Note that **E** is a sheaf of \mathcal{O}_M -modules. On a trivializing neighborhood U,

$$E|_U \cong U \times \mathbb{C}^l$$
,

so that $\Gamma(U, \mathbf{E}) \cong \bigoplus_l \mathcal{O}_M(U)$. This implies that \mathbf{E} is a locally free sheaf of complex rank l over M. (We will henceforth follow the convention of denoting the sheaf of GH sections of a GH vector bundle by the corresponding bold letter.)

Conversely, given any locally free sheaf \mathcal{F} of \mathcal{O}_M -modules of rank l, one can construct an SGH vector bundle in the following manner. Let $\{U_\alpha\}$ be a covering of M such that $\mathcal{F}|_{U_\alpha}$ is free and

$$\widehat{\psi_{lpha}}:\mathcal{F}|_{U_{lpha}}\longrightarrow \bigoplus_{l}\mathcal{O}_{U_{lpha}}\,,$$

is the corresponding isomorphism. Now consider the isomorphism of sheaves of modules

$$\widehat{\psi_{\alpha\beta}} = \widehat{\psi_{\alpha}} \circ (\widehat{\psi_{\beta}}^{-1}) : \bigoplus_{l} \mathcal{O}_{U_{\alpha} \cap U_{\beta}} \longrightarrow \bigoplus_{l} \mathcal{O}_{U_{\alpha} \cap U_{\beta}}.$$

Since every endomorphism of $\bigoplus_l \mathcal{O}_{U_{\alpha}}$ is represented by an $l \times l$ matrix, $\widehat{\psi_{\alpha\beta}}$ defines an $l \times l$ matrix $(\phi_{\alpha\beta})$ whose elements are GH functions over $U_{\alpha} \cap U_{\beta}$. One can check that the matrices satisfy the cocycle conditions and thus they can be regarded as the transition maps of an SGH vector bundle $E_{\mathcal{F}}$ of real rank 2l over M such that

$$\mathbf{E}_{\mathcal{F}} \cong \mathcal{F}$$
 as \mathcal{O}_M -modules.

Hence, we get the following.

Proposition 4.6. Let M be a GC manifold and $l \in \mathbb{N}$. Consider the following set

 $\mathscr{S}_{l} := Set \ of \ all \ isomorphism \ class \ of \ locally \ free \ \mathcal{O}_{M}$ -modules of $complex \ rank \ l$.

Then the association $E \longrightarrow \mathbf{E}$ induces an one to one correspondence between \mathscr{E}_l and \mathscr{S}_l where \mathscr{E}_l as given in Proposition 4.5. The inverse map is given by the association $\mathcal{F} \longrightarrow E_{\mathcal{F}}$.

5. Generalized Holomorphic Connection on SGH Principal bundle

5.1. GH tangent and GH cotangent bundle

Let (M, \mathcal{J}_M) be a regular GC manifold of type $k \in \mathbb{N} \cup \{0\}$. Let L_M and $\overline{L_M}$ are its corresponding +i and -i-eigenspace sub-bundles of $(TM \oplus T^*M) \otimes \mathbb{C}$ respectively. Define

$$\mathcal{G}^*M := L_M \cap \left(T^*M \otimes \mathbb{C}\right).$$
(5.1)

By [22, Proposition 3.13], \mathcal{G}^*M is an SGH vector bundle over M. It is called the *GH* cotangent bundle. The GH sections of \mathcal{G}^*M are called GH 1-forms. Since \mathcal{G}^*M is *B*-field transformation invariant, locally (cf. (2.10), (2.11)), the space of GH 1-forms is of the form

$$\operatorname{Span}_{\mathcal{O}_U} \{ dz_1 \cdots dz_k \}$$

This shows that $\mathcal{G}^*\mathbf{M}$, the sheaf of GH sections of \mathcal{G}^*M , is a locally free sheaf of \mathcal{O}_M -modules of finite rank k. Define

$$\mathcal{G}\mathbf{M} := \operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}^*\mathbf{M}, \mathcal{O}_M).$$
(5.2)

Since $\mathcal{G}^*\mathbf{M}$ is a locally free sheaf of \mathcal{O}_M -modules of rank k, $\mathcal{G}\mathbf{M}$ will also be a locally free sheaf with the same rank. Then, by Proposition 4.6, the corresponding SGH vector bundle is defined as

$$\mathcal{G}M := E_{\mathcal{G}\mathbf{M}} \,. \tag{5.3}$$

Here $\mathcal{G}M$ as given in Proposition 4.6. It is called *GH tangent bundle*. The GH sections of $\mathcal{G}M$ are called GH vector fields. Since \mathcal{G}^*M is *B*-transformation invariant, $\mathcal{G}M$ is also invariant under *B*-transformation. Thus, locally (cf. (2.10)), the space of GH vector fields is of the form

$$\operatorname{Span}_{\mathcal{O}_U}\left\{\frac{\partial}{\partial z_1}, \cdots, \frac{\partial}{\partial z_k}\right\}$$

Note that $\mathcal{G}M$ and \mathcal{G}^*M are dual to each other as \mathcal{O}_M -modules of their GH sections. But, we can say more. One can see that $C^{\infty}(\mathcal{G}M) = \mathcal{G}\mathbf{M} \otimes_{\mathcal{O}_M} C_M^{\infty}$. Then

$$C^{\infty}(\mathcal{G}^{*}M) = \mathcal{G}^{*}\mathbf{M} \otimes_{\mathcal{O}_{M}} C_{M}^{\infty}$$

$$\cong \operatorname{Hom}_{\mathcal{O}_{M}}(\mathcal{G}\mathbf{M}, \mathcal{O}_{M}) \otimes_{\mathcal{O}_{M}} C_{M}^{\infty}$$

$$\cong \operatorname{Hom}_{\mathcal{O}_{M} \otimes_{\mathcal{O}_{M}} C_{M}^{\infty}}(\mathcal{G}\mathbf{M} \otimes_{\mathcal{O}_{M}} C_{M}^{\infty}, \mathcal{O}_{M} \otimes_{\mathcal{O}_{M}} C_{M}^{\infty})$$
(by [7, Proposition 7, Section 5, Chapter II])
$$= \operatorname{Hom}_{C_{M}^{\infty}}(C^{\infty}(\mathcal{G}M), C_{M}^{\infty})$$

$$= C^{\infty}((\mathcal{G}M)^{*}).$$
(5.4)

Here, $(\mathcal{G}M)^*$ is the dual SGH vector bundle of $\mathcal{G}M$. This shows that $\mathcal{G}M$ and \mathcal{G}^*M are also dual to each other as C_M^∞ -modules of their smooth sections, that is, they are dual to each other as complex vector bundles over M.

Remark 5.1. We note that the definition of $\mathcal{G}M$, given in [22, p.16], as $\mathcal{G}M := \overline{L} \cap TM \otimes \mathbb{C}$ is flawed as it varies with *B*-transformations. In other words, it is not always the case that $\mathcal{G}M$ and $e^B(\overline{L}_M) \cap TM \otimes \mathbb{C}$ are same, while $\mathcal{G}^*M = e^B(L_M) \cap T^*M \otimes \mathbb{C}$ for any *B*-transformation. Therefore, this does not guarantee duality with respect to \mathcal{G}^*M .

5.2. SGH principal bundles with complex fibers and GH connections

There are some special properties of SGH principal bundles with a complex Lie group as a structure group which we similar to holomorphic principal bundles over complex manifolds. These properties do not hold in general. We list a few of them here that are important for our purposes.

Proposition 5.2. Let $G \hookrightarrow P \xrightarrow{\pi} M$ be an SGH principal G-bundle over a regular GC manifold (M, \mathcal{J}_M) where G is a complex Lie group. Then

- (1) P admits GH sections over any trivializing open set $U \subseteq M$.
- (2) If $s: V \to P$ is a GH section of P over an open subset $V \subseteq M$, then so is $s \cdot \phi$ for any GH map $\phi: V \to G$.
- (3) If s_1 and s_2 are any two GH sections of P over V, then there exists a unique GH map $\phi: V \to G$ such that $s_2 = s_1 \cdot \phi$.

Proof. First, note that it suffices to prove the statement of the theorem for a local trivialization of P as a GH homeomorphism is a GH map. Additionally, by Proposition 3.9, any GH map between complex manifolds is simply a holomorphic map and vice versa.

Then, (1) follows from the fact that a constant map from $c : U \to G$ is GH by Proposition 3.9 as $c_* = 0$. This implies that the local trivialization of P over U admits a GH section.

Part (2) follows from the fact that the right action of G on itself is GH if G is a complex Lie group, and that the composition of GH maps is a GH map.

Part (3) follows from the fact that inversion operation in a complex Lie group, is a GH map, in fact, a GH homeomorphism. \Box

By Remark 4.2, G acts on P as a group of fiber preserving GH automorphisms, $P \times G \longrightarrow P$. The GCS induced by the complex structure on G is regular, which implies that P is a regular GC manifold. Let \mathcal{G}^*P and $\mathcal{G}P$ denote the GH cotangent and GH tangent bundles of G as specified in (5.1) and (5.3), respectively. Since G acts on P, it has an induced action on $(TP \oplus T^*P) \otimes \mathbb{C}$. For any $g \in G$, we have

$$(X+\xi) \cdot g = \begin{pmatrix} g_*^{-1} & 0\\ 0 & g^* \end{pmatrix} (X+\xi) \quad \text{for all} \quad X+\xi \in (TP \oplus T^*P) \otimes \mathbb{C}$$

As $g: P \longrightarrow P$, $p \mapsto p \cdot g$, is a GH automorphism for every $g \in G$, it follows that G acts on *i*-eigen bundle L_P of \mathcal{J}_P . This implies that G acts on \mathcal{G}^*P and hence on $\mathcal{G}P$. Define the *Atiyah bundle* of P by

$$At(P) := \mathcal{G}P/G. \tag{5.5}$$

Then, a point of At(P) is a field of GH tangent vectors, defined along one of the fibers of P, which is invariant under G. We shall show that At(P) has a natural SGH vector bundle structure over M.

Let $m \in M$ and let $U \subset M$ be a sufficiently small open neighborhood of m such that there exist a GH section of P over U,

$$s: U \longrightarrow P$$
. (5.6)

Let $(\mathcal{G}P)_s$ be the restriction of $\mathcal{G}P$ to s(U). Now since $s: U \longrightarrow s(U)$ is a diffeomorphism, s(U) can be endowed with the structure of a regular GC manifold such that s becomes a GH homeomorphism between U and s(U). Since s is a GH section, by [22, Example 3.3], $s^*(\mathcal{G}P)$ is an SGH vector bundle over U and so, $(s^{-1})^*(s^*(\mathcal{G}P))$ is also an SGH vector bundle over s(U) which coincides with $(\mathcal{G}P)_s$ as a smooth bundle. This defines a canonical SGH bundle structure on $(\mathcal{G}P)_s$.

There is a natural one-to-one correspondence between $At(P)_U$ and $(\mathcal{G}P)_s$,

$$\gamma_s : At(P)_U \longrightarrow (\mathcal{G}P)_s \,, \tag{5.7}$$

where γ_s assigns to each invariant GH vector field along $\pi^{-1}(x) := P_x$ its value at s(x). This is easily seen to be an isomorphism of smooth vector bundles. Then, the SGH vector bundle structure of $(\mathcal{G}P)_s$ defines an SGH vector bundle structure of $At(P)_U$.

It remains to show that this construction is independent of the choice of the GH section s. Let s_1 and s_2 be any two GH sections of P over U. Then, by Proposition 5.2, there exist a unique GH map $\phi: U \longrightarrow G$ such that

$$s_1(x) \cdot \phi(x) = s_2(x), \quad \forall \ x \in U.$$

Note that the map $\psi: U \times G \longrightarrow U \times G$ defined as

$$\psi(x,g) = (x,\phi(x) \cdot g) \text{ for all } (x,g) \in U \times G$$

is a GH automorphism of $U \times G$ by Proposition 4.4. Therefore, ψ induces an isomorphism of SGH vector bundles, again denoted by ψ ,

$$\psi: (\mathcal{G}P)_{s_1} \longrightarrow (\mathcal{G}P)_{s_2}$$

satisfying

$$\gamma_{s_2} = \psi \circ \gamma_{s_1}$$
 .

Hence, the SGH vector bundle structure on At(P) is well-defined.

Let \mathcal{T} denote the sub-bundle of TP formed by vectors tangential to the fibers of P. Define $\mathcal{GT} = \mathcal{T} \cap \mathcal{GP}$. Since G acts on \mathcal{T} , it also acts on \mathcal{GT} . Define

$$\mathcal{R} = \mathcal{GT}/G. \tag{5.8}$$

If γ_s is defined as in (5.7), then restricting to \mathcal{R}_U , we get

$$\gamma_s|_{\mathcal{R}_U} := \gamma'_s : \mathcal{R}_U \longrightarrow (\mathcal{GT})_s \,. \tag{5.9}$$

Note that $(\mathcal{GT})_s$ is also an SGH vector sub-bundle of $(\mathcal{GP})_s$ as (\mathcal{GT}) is an SGH vector sub-bundle of (\mathcal{GP}) . Hence by above, \mathcal{R} is also an SGH sub-bundle of At(P).

We now examine \mathcal{R} more closely. Let \mathfrak{g} denote the complex Lie algebra of G. As a vector space, \mathfrak{g} is the holomorphic tangent space of G at identity. In the SGH principal bundle P, for $x \in M$, each fiber P_x can be identified with G up to a left multiplication. Note that each smooth tangent vector at the point $p \in P$, tangential to the fiber, defines a unique left-invariant smooth vector field on G. Since the left (respectively, right) multiplication is biholomorphic, the vector space of left (respectively, right) invariant holomorphic vector fields on G is then isomorphic with \mathfrak{g} via left (respectively, right) multiplication. Note that by the locally product nature of the GCS on P, and the absence of a B transformation in a GH homeomorphism, any holomorphic tangent vector to the fiber at the point $p \in P$ defines a unique left invariant GH tangent vector field on G. Thus, we have an SGH vector bundle isomorphism

$$\mathcal{GT} \cong P \times \mathfrak{g}$$

Then, the action of G on \mathcal{GT} induces an action on $P \times \mathfrak{g}$ as follows,

$$(p,l) \cdot g = (p \cdot g, \operatorname{Ad}(g^{-1}) \cdot l) \quad \forall \ (p,l) \in P \times \mathfrak{g}.$$
 (5.10)

Let $P \times_G \mathfrak{g}$ be the identification space defined by the action in (5.10). The adjoint map is a biholomorphism due to the complex Lie group structure of G. Consequently, the transition maps of the complex vector bundle $P \times_G \mathfrak{g}$ are GH maps. Therefore, by Theorem 3.2 and [22, Proposition 3.2], $P \times_G \mathfrak{g}$ is an SGH vector bundle over M with fiber \mathfrak{g} associated to P by the adjoint representation. Hence, $\mathcal{R} = \mathcal{GT}/G \cong P \times_G \mathfrak{g}$. We shall denote it by Ad(P), that is,

$$Ad(P) := P \times_G \mathfrak{g}. \tag{5.11}$$

The projection $\pi : P \longrightarrow M$ induces a bundle map $\mathcal{G}\pi : At(P) \longrightarrow \mathcal{G}M$. Using Definition 3.1, we deduce that $\mathcal{G}\pi$ is an SGH vector bundle homomorphism.

Moreover, let T_s denote the tangent bundle and $\mathcal{G}T_s$ denotes the GH tangent bundle of s(U) respectively where s(U) is the image of the GH section s as in (5.6). Then we have $(\mathcal{G}P)_s = (\mathcal{G}\mathcal{T})_s \oplus (\mathcal{G}T_s)$ where $(\mathcal{G}P)_s$ and $(\mathcal{G}\mathcal{T})_s$ are as defined in (5.7) and (5.9), respectively. This implies the following commutative diagram:

$$0 \longrightarrow \mathcal{R}_{U} \xrightarrow{\xi} At(P)_{U} \xrightarrow{\mathcal{G}_{\pi}} \mathcal{G}U \longrightarrow 0$$
$$\downarrow^{\gamma'_{s}} \qquad \downarrow^{\gamma_{s}} \qquad \downarrow^{s^{\#}} 0 \longrightarrow (\mathcal{G}\mathcal{T})_{s} \longrightarrow (\mathcal{G}P)_{s} \longrightarrow \mathcal{G}T_{s} \longrightarrow 0$$

where γ_s , γ'_s and ξ are as in (5.7), (5.9) and the natural inclusion map, respectively. Also, the map $s^{\#} : \mathcal{G}U \longrightarrow \mathcal{G}T_s$, induced by s, is an isomorphism of SGH vector bundles. We conclude that

$$0 \longrightarrow \mathcal{R} \xrightarrow{\xi} At(P) \xrightarrow{\mathcal{G}\pi} \mathcal{G}M \longrightarrow 0$$

is a short exact sequence of SGH vector bundles over M. We summarize our results in the following theorem.

Theorem 5.3. Let P be an SGH principal G-bundle over a regular GC manifold (M, \mathcal{J}_M) where G is a complex Lie group. Then, there exists a canonical short exact sequence $\mathcal{A}(P)$ of SGH vector bundles over M:

$$0 \longrightarrow Ad(P) \longrightarrow At(P) \longrightarrow \mathcal{G}M \longrightarrow 0$$
(5.12)

where $\mathcal{G}M$ is the GH tangent bundle of M as in (5.3), Ad(P) is the SGH vector bundle associated to P by the adjoint representation of G as in (5.11), and At(P) is the SGH vector bundle of invariant GH tangent vector fields on P as in (5.5).

Definition 5.4. Let P be an SGH principal G-bundle over a regular GC manifold M where G is a complex Lie group. A generalized holomorphic (GH) connection on P is a splitting of the short exact sequence $\mathcal{A}(P)$ in (5.12) such that the splitting map is a GH map.

By [3, Proposition 2], the extension $\mathcal{A}(P)$ defines an element

 $a(P) \in H^1(M, \operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}, \operatorname{Ad}(\mathbf{P}))),$

and $\mathcal{A}(P)$ is a trivial extension if and only if a(P) = 0.

Note that $\mathcal{G}^*\mathbf{M} = \operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}, \mathcal{O}_M)$. Hence,

 $\operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}\,,\,\mathbf{Ad}(\mathbf{P}))=\mathbf{Ad}(\mathbf{P})\otimes_{\mathcal{O}_M}\mathcal{G}^*\mathbf{M}\,.$

Thus we have the following result.

Theorem 5.5. An SGH principal G-bundle P over a regular GC manifold M defines an element

$$a(P) \in H^1(M, \operatorname{Ad}(\mathbf{P}) \otimes_{\mathcal{O}_M} \mathcal{G}^*\mathbf{M})$$

P admits a GH connection if and only if a(P) = 0.

Definition 5.6. The element a(P) in Theorem 5.5 is called the *Atiyah class* of the SGH principal *G*-bundle *P*. The SGH vector bundle At(P) in (5.12) is called the *SGH Atiyah bundle* of the SGH principal *G*-bundle *P*.

Definition 5.7. A smooth generalized connection in the principal bundle P is a smooth splitting of the short exact sequence $\mathcal{A}(P)$ in (5.12).

Remark 5.8. In this case, when $\mathcal{A}(P)$ is considered as a short exact sequence of smooth vector bundles, again by [3, Proposition 2], the smooth extension $\mathcal{A}(P)$ defines an element

$$a'(P) \in H^1(M, \operatorname{Hom}_{C^{\infty}_M}(C^{\infty}(\mathcal{G}M), C^{\infty}(Ad(P))))$$

and $\mathcal{A}(P)$ is a trivial smooth extension if and only if a'(P) = 0. But due to the partition of unity of smooth functions, we can see that $\operatorname{Hom}_{C_M^{\infty}}(C^{\infty}(\mathcal{G}M), C^{\infty}(Ad(P)))$ is a fine sheaf. Thus $H^1(M, \operatorname{Hom}_{C_M^{\infty}}(C^{\infty}(\mathcal{G}M), C^{\infty}(Ad(P))) = 0$ and so a'(P) will always be zero. This implies that a smooth generalized connection always exists.

5.3. Local coordinate description of the Atiyah class

In this section, we compute the Atiyah class a(P) in local coordinates following Atiyah [3]. Let G be a connected complex Lie group with real Lie algebra \mathfrak{g} . Let P be an SGH principal G-bundle over a regular GC manifold M with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ and transition maps $\phi_{\alpha\beta}$ (see (4.2)).

Let $M_{\mathfrak{g}} := M \times \mathfrak{g}$ denote the trivial SGH vector bundle over M where \mathfrak{g} is the complex Lie algebra of G. Since ϕ_{α} is a GH homeomorphism and it commutes with the action of G, it induces an SGH vector bundle isomorphism

$$\widehat{\phi_{\alpha}} : At(P)|_{U_{\alpha}} \longrightarrow \mathcal{G}M|_{U_{\alpha}} \oplus M_{\mathfrak{g}}|_{U_{\alpha}} .$$
(5.13)

Define the SGH vector bundle homomorphism

$$a_{\alpha}: \mathcal{G}M|_{U_{\alpha}} \longrightarrow At(P)|_{U_{\alpha}} \tag{5.14}$$

by $a_{\alpha}(X) = (\widehat{\phi_{\alpha}})^{-1}(X \oplus 0)$ for all $X \in \mathcal{G}M|_{U_{\alpha}}$. Then the map $a_{\alpha\beta} : \mathcal{G}M|_{U_{\alpha\beta}} \longrightarrow At(P)|_{U_{\alpha\beta}}$, defined as

$$a_{\alpha\beta} = a_\beta - a_\alpha$$

gives a representative 1-cocycle for a(P) in $H^1(M, \operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}, \operatorname{\mathbf{Ad}}(\mathbf{P}))$.

Denote $G_{\mathfrak{g}} := G \times \mathfrak{g}$. Note that $\mathcal{G}G := T^{1,0}G$. Both right and left multiplication maps on G are biholomorphic. Using them we have SGH bundle isomorphisms

 $\xi: \mathcal{G}G \longrightarrow G_{\mathfrak{g}} \quad \text{and} \quad \eta: \mathcal{G}G \longrightarrow G_{\mathfrak{g}},$

respectively. Thus,

 $\xi\,,\,\eta\in H^0(G,\operatorname{Hom}_{\mathcal{O}_G}(\mathbf{T^{1,0}G},\mathbf{G}_\mathfrak{g}))\,.$

Now, $\phi_{\alpha\beta}$ is a GH map due to Proposition 4.4, thereby it induces elements

$$\xi_{\alpha\beta}, \eta_{\alpha\beta} \in \Gamma(U_{\alpha\beta}, \operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}, \mathbf{M}_{\mathfrak{g}}))$$

Then, for each $X \in \mathcal{G}M|_{U_{\alpha\beta}}$,

$$\widehat{\phi_{\alpha}}(a_{\alpha\beta}(X)) = \widehat{\phi_{\alpha}}((\widehat{\phi_{\beta}})^{-1}(X \oplus 0) - (\widehat{\phi_{\alpha}})^{-1}(X \oplus 0))$$
$$= \widehat{\phi_{\alpha}}((\widehat{\phi_{\beta}})^{-1}(X \oplus 0)) - (X \oplus 0)$$
$$= (X \oplus \xi_{\alpha\beta}(X)) - (X \oplus 0)$$
$$= (0 \oplus \xi_{\alpha\beta}(X)).$$

By the short exact sequence in (5.12), we can identify $Ad(P)|_{U_{\alpha}}$ as an SGH subbundle of $At(P)|_{U_{\alpha}}$. Then, the SGH vector bundle isomorphism between $Ad(P)|_{U_{\alpha\beta}}$ and $M_{\mathfrak{g}}|_{U_{\alpha}}$ is identified with the restriction map

$$\phi_{\alpha}|_{Ad(P)|_{U_{\alpha}}} : Ad(P)|_{U_{\alpha}} \longrightarrow M_{\mathfrak{g}}|_{U_{\alpha}}.$$

Therefore, we get

$$a_{\alpha\beta} = (\widehat{\phi}_{\alpha})^{-1} \circ \xi_{\alpha\beta} \,, \tag{5.15}$$

and since $\xi_{\alpha\beta} = \operatorname{Ad}(\phi_{\alpha\beta}) \cdot \eta_{\alpha\beta}$, we can replace (5.15) by

$$a_{\alpha\beta} = (\widehat{\phi_{\beta}})^{-1} \circ \eta_{\alpha\beta} \,. \tag{5.16}$$

Now if a(P) = 0, then the coboundary equation is

$$a_{\alpha\beta} = \gamma_\beta - \gamma_\alpha$$

where $\gamma_i \in \Gamma(U_i, \operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}, \operatorname{\mathbf{Ad}}(\mathbf{P})))$ for $i \in \{\alpha, \beta\}$. For each $i \in \{\alpha, \beta\}$, if we denote

$$\Theta_i := \widehat{\phi_i} \circ \gamma_i$$

then $\Theta_i \in \Gamma(U_i, \operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}, \mathbf{M}_{\mathfrak{g}}))$. Thus the coboundary equation becomes

$$\xi_{\alpha\beta} = \operatorname{Ad}(\phi_{\alpha\beta}) \cdot \Theta_{\beta} - \Theta_{\alpha} , \qquad (5.17)$$

or

$$\eta_{\alpha\beta} = \Theta_{\beta} - \operatorname{Ad}(\phi_{\beta\alpha}) \cdot \Theta_{\alpha} \,. \tag{5.18}$$

Remark 5.9. Note that, in case of smooth generalized connection, since we have

$$H^1(M, \operatorname{Hom}_{C^{\infty}_M}(C^{\infty}(\mathcal{G}M), C^{\infty}(Ad(P))) = 0,$$

the co boundary equation is

$$a_{\alpha\beta} = \gamma'_{\beta} - \gamma'_{\alpha}$$

where $\gamma'_i \in C^{\infty}(U_i, \operatorname{Hom}_{C^{\infty}_M}(C^{\infty}(\mathcal{G}M), C^{\infty}(Ad(P))))$ for $i \in \{\alpha, \beta\}$. Then for each i in $\{\alpha, \beta\}$, if we again denote

$$\Theta_i := \widehat{\phi}_i \circ \gamma'_i \,,$$

we get that $\Theta_i \in C^{\infty}(U_i, \operatorname{Hom}_{C^{\infty}_M}(C^{\infty}(\mathcal{G}M), C^{\infty}(M_{\mathfrak{g}})))$. Thus the co-boundary equation becomes

$$\xi_{\alpha\beta} = \operatorname{Ad}(\phi_{\alpha\beta}) \cdot \Theta_{\beta} - \Theta_{\alpha} , \qquad (5.19)$$

or

$$\eta_{\alpha\beta} = \Theta_{\beta} - \operatorname{Ad}(\phi_{\beta\alpha}) \cdot \Theta_{\alpha} \,. \tag{5.20}$$

6. Atiyah class of an SGH vector bundle

Let E be an SGH vector bundle over a regular GC manifold M with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$. Let $J^{1}(E)$ be the first jet bundle of E over M as defined in [22, Section 3.2]. Then by [22, Theorem 3.17], $J_{1}(E)$ is an SGH vector bundle over M and it fits into the following exact sequence, denoted by $\mathcal{B}(E)$,

$$0 \longrightarrow \mathcal{G}^* M \otimes E \xrightarrow{J} J_1(E) \xrightarrow{\pi_1} E \longrightarrow 0$$
(6.1)

of SGH vector bundles over M.

As a sheaf of \mathbb{C} -modules,

$$\mathbf{J}_{\mathbf{1}}(\mathbf{E}) = \mathbf{E} \oplus_{\mathbb{C}} (\mathcal{G}^* \mathbf{M} \otimes_{\mathcal{O}_M} \mathbf{E})$$

Recall that, for each $m \in M$, $f \in \mathcal{O}_{M,m}$ if and only if $(df)_m \in (\mathcal{G}^*M)_m$. So, we can define the map

$$\phi_m: \mathcal{O}_{M,m} \times \mathbf{J_1(E)}_m \longrightarrow \mathbf{J_1(E)}_m$$

by

$$\phi_m(f,s+\delta) = fs \oplus (f\delta + df \otimes s)$$

where $s \in E_m$, $\delta \in ((\mathcal{G}^*M)_m \otimes_{\mathcal{O}_{M,m}} E_m)$, and $f \in \mathcal{O}_{M,m}$. This defines an action of \mathcal{O}_M on $\mathbf{J}_1(\mathbf{E})$ making it a sheaf of \mathcal{O}_M -modules. We obtain the following short exact sequence of \mathcal{O}_M -modules

$$0 \longrightarrow \mathcal{G}^* \mathbf{M} \otimes_{\mathcal{O}_M} \mathbf{E} \xrightarrow{\widehat{J}} \mathbf{J}_1(\mathbf{E}) \xrightarrow{\widehat{\pi}_1} \mathbf{E} \longrightarrow 0$$
(6.2)

where $\widehat{J}(\delta) = 0 + \delta$ and $\widehat{\pi}_1(s + \delta) = s$ are the morphisms of \mathcal{O}_M -modules induced by the maps J and π_1 in (6.1), respectively.

Since $\operatorname{Hom}_{\mathcal{O}_M}(\mathbf{E}, \mathcal{G}^*\mathbf{M} \otimes_{\mathcal{O}_M} \mathbf{E}) \cong \mathcal{G}^*\mathbf{M} \otimes_{\mathcal{O}_M} \operatorname{End}(\mathbf{E})$, by [3, Proposition 2] and using (6.2), the extension $\mathcal{B}(E)$ defines an element

$$b(E) \in H^1(M, \mathcal{G}^*\mathbf{M} \otimes_{\mathcal{O}_M} \operatorname{End}(\mathbf{E}))$$

Definition 6.1. ([22, Definition 4.4]) b(E) is called the *Atiyah class* of the SGH vector bundle E over M.

The following result is standard in the holomorphic case (see [3, Proposition 9]) and follows similarly in the SGH setting.

Proposition 6.2. Let E be an SGH vector bundle of real rank 2l over M. Let P_E be the corresponding SGH principal $GL_l(\mathbb{C})$ -bundle as in (4.3). Then we have

$$\operatorname{End}(E) \cong Ad(P_E)$$

as SGH vector bundles where $Ad(P_E)$ as in (5.11).

Corollary 6.3. $H^1(M, \mathcal{G}^*\mathbf{M} \otimes_{\mathcal{O}_M} \operatorname{End}(\mathbf{E})) \cong H^1(M, \mathcal{G}^*\mathbf{M} \otimes_{\mathcal{O}_M} \operatorname{Ad}(\mathbf{P}_{\mathbf{E}})).$

Theorem 6.4. Let E be an SGH vector bundle over a regular GC manifold M. Let P be the associated SGH principal $GL_l(\mathbb{C})$ -bundle over M, as in (4.4), where l is the complex rank of E. Let b(E) and a(P) be the obstruction elements defined by $\mathcal{B}(E)$ and $\mathcal{A}(P)$, as in the equations (6.1) and (5.12), respectively. Then

$$a(P) = -b(E) \,.$$

Proof. Let E be an SGH vector bundle with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ where

$$\phi_{\alpha}: E|_{U_{\alpha}} \longrightarrow U_{\alpha} \times \mathbb{C}^{l} , \qquad (6.3)$$

are local GH homeomorphisms (cf. (4.1)). Then P is defined by the transition functions (cf. (4.2)),

$$\phi_{\alpha\beta}: U_{\alpha\beta} \longrightarrow GL_l(\mathbb{C}) , \qquad (6.4)$$

where

$$\psi_{\alpha\beta} = \phi_{\alpha} \circ \phi_{\beta}^{-1} : U_{\alpha\beta} \times GL_{l}(C) \longrightarrow U_{\alpha\beta} \times GL_{l}(\mathbb{C})$$
(6.5)

is given by $\psi_{\alpha\beta}(m,g) = (m, \phi_{\alpha\beta}(m)g).$

Let $W = \mathbb{C}^l$ so that $E \cong P \times_{GL_l(\mathbb{C})} W$. Let $M_W = M \times W$, a trivial SGH vector bundle over M. The GH homeomorphism ϕ_{α} induces a sheaf isomorphism of $\mathcal{O}_M|_{U_{\alpha}}$ -modules

$$\widetilde{\phi}_{\alpha}: \mathbf{E}|_{U_{\alpha}} \longrightarrow \mathbf{M}_{\mathbf{W}}|_{U_{\alpha}}.$$
(6.6)

This also induces another canonical $\mathcal{O}_M|_{U_{\alpha}}$ -module isomorphism, again denoted by ϕ_{α} ,

$$\widetilde{\phi}_{\alpha} = \widetilde{\phi}_{\alpha} \otimes_{\mathcal{O}_M} \mathrm{Id} : \mathbf{E}|_{U_{\alpha}} \otimes_{\mathcal{O}_M|_{U_{\alpha}}} \mathcal{G}^* \mathbf{M}|_{U_{\alpha}} \longrightarrow \mathbf{M}_{\mathbf{W}}|_{U_{\alpha}} \otimes_{\mathcal{O}_M|_{U_{\alpha}}} \mathcal{G}^* \mathbf{M}|_{U_{\alpha}} \,. \tag{6.7}$$

Note that $f \in \mathcal{O}_M$ if and only if $df \in \mathcal{G}^*\mathbf{M}$. Thus the exterior derivative map $d : \mathcal{O}_M \longrightarrow \mathcal{G}^*\mathbf{M}$ is well-defined. Since M_W is a trivial bundle,

$$\mathbf{M}_{\mathbf{W}}|_{U_{\alpha}} \cong_{\mathcal{O}_M|_{U_{\alpha}}} \bigoplus_{r} \mathcal{O}_M|_{U_{\alpha}}$$
(6.8)

for some $r \in \mathbb{N}$. Thus we can extend d to a \mathbb{C} -linear sheaf homomorphism,

 $d: \mathbf{M}_{\mathbf{W}}|_{U_{\alpha}} \longrightarrow \mathbf{M}_{\mathbf{W}}|_{U_{\alpha}} \otimes_{\mathcal{O}_{M}|_{U_{\alpha}}} \mathcal{G}^{*}\mathbf{M}|_{U_{\alpha}}.$ (6.9)

Define a \mathbb{C} -homomorphism of sheaves over U_{α} ,

$$D_{\alpha}: \mathbf{E}|_{U_{\alpha}} \longrightarrow \mathbf{E}|_{U_{\alpha}} \otimes_{\mathcal{O}_M|_{U_{\alpha}}} \mathcal{G}^* \mathbf{M}|_{U_{\alpha}}$$
(6.10)

by

 $D_{\alpha}(s) = (\widetilde{\phi}_{\alpha})^{-1} d\widetilde{\phi}_{\alpha}(s)$

where the first ϕ_{α} , d and the second ϕ_{α} are as in the equations (6.7), (6.9) and (6.6), respectively. Now consider the sheaf homomorphism

$$b_{\alpha}: \mathbf{E}|_{U_{\alpha}} \longrightarrow \mathbf{J}_{\mathbf{1}}(\mathbf{E})|_{U_{\alpha}}$$

$$(6.11)$$

defined by

 $b_{\alpha}(s) = s + D_{\alpha}(s) \quad \text{for all } s \in \mathbf{E}|_{U_{\alpha}}.$

Then for any $f \in \mathcal{O}_M|_{U_\alpha}$ and $s \in \mathbf{E}|_{U_\alpha}$, we have

$$b_{\alpha}(fs) = fs + (\widetilde{\phi}_{\alpha})^{-1} d\widetilde{\phi}_{\alpha}(fs)$$

= $fs \oplus (s \otimes df + f(\widetilde{\phi}_{\alpha})^{-1} d\widetilde{\phi}_{\alpha}(s))$
= $f \cdot (s + D_{\alpha}(s))$.

Hence, b_{α} is an \mathcal{O}_M -module homomorphism. Consider the sheaf homomorphism

$$b_{\alpha\beta}: \mathbf{E}|_{U_{\alpha\beta}} \longrightarrow \mathbf{J}_{\mathbf{1}}(\mathbf{E})|_{U_{\alpha\beta}}$$
 (6.12)

defined by $b_{\alpha\beta} := b_{\beta} - b_{\alpha}$. Note that $b_{\alpha\beta}(s) = D_{\beta}(s) - D_{\alpha}(s)$. So

$$b_{\alpha\beta} \in \Gamma(U_{\alpha\beta}, \operatorname{Hom}_{\mathcal{O}_M}(\mathbf{E}, \mathbf{E} \otimes_{\mathcal{O}_M} \mathcal{G}^*\mathbf{M}))$$

This shows that $\{b_{\alpha\beta}\}$ is a representative 1-cocycle for b(E) in $H^1(M, \operatorname{End}(\mathbf{E}) \otimes_{\mathcal{O}_M} \mathcal{G}^*\mathbf{M})$.

Consider the following two sheaf homomorphisms over U_{α} ,

$$\widetilde{\phi}_{\alpha\beta} = \widetilde{\phi}_{\alpha} \circ (\widetilde{\phi}_{\beta})^{-1} : \mathbf{M}_{\mathbf{W}}|_{U_{\alpha\beta}} \longrightarrow \mathbf{M}_{\mathbf{W}}|_{U_{\alpha\beta}}, \qquad (6.13)$$

and the second one, also denoted by $\widetilde{\phi}_{\alpha\beta}$,

$$\widetilde{\phi}_{\alpha\beta}: \mathbf{M}_{\mathbf{W}}|_{U_{\alpha\beta}} \otimes_{\mathcal{O}_M|_{U_{\alpha\beta}}} \mathcal{G}^* \mathbf{M}|_{U_{\alpha\beta}} \longrightarrow \mathbf{M}_{\mathbf{W}}|_{U_{\alpha\beta}} \otimes_{\mathcal{O}_M|_{U_{\alpha\beta}}} \mathcal{G}^* \mathbf{M}|_{U_{\alpha\beta}}.$$
(6.14)

By (6.8), we can see that $\tilde{\phi}_{\alpha\beta}$ can be thought of as a $\mathcal{O}_M|_{U_{\alpha\beta}}$ -valued matrix, again denoted by

$$\widetilde{\phi}_{\alpha\beta}: \bigoplus_r \mathcal{O}_M|_{U_{\alpha\beta}} \longrightarrow \bigoplus_r \mathcal{O}_M|_{U_{\alpha\beta}}.$$

So $d(\widetilde{\phi}_{\alpha\beta})$ is well understood. Then for any $s \in \mathbf{M}_{\mathbf{W}}|_{U_{\alpha\beta}}$, we get

$$\widetilde{\phi}_{\alpha}b_{\alpha\beta}(\widetilde{\phi}_{\alpha})^{-1}(s) = \widetilde{\phi}_{\alpha}(D_{\beta}((\widetilde{\phi}_{\alpha})^{-1}(s)) - D_{\alpha}((\widetilde{\phi}_{\alpha})^{-1}(s)))$$

$$= \widetilde{\phi}_{\alpha}((\widetilde{\phi}_{\beta})^{-1}d(\widetilde{\phi}_{\beta}(\widetilde{\phi}_{\alpha})^{-1}(s)) - (\widetilde{\phi}_{\alpha})^{-1}(ds))$$

$$= \widetilde{\phi}_{\alpha\beta}(d(\widetilde{\phi}_{\alpha\beta}^{-1}(s)) - ds \qquad (6.15)$$

$$= \widetilde{\phi}_{\alpha\beta} d(\widetilde{\phi}_{\alpha\beta}^{-1}) \cdot s$$

$$= -d(\widetilde{\phi}_{\alpha\beta}) \widetilde{\phi}_{\alpha\beta}^{-1} \cdot s.$$

But, in the notation of Subsection 5.3, $d(\tilde{\phi}_{\alpha\beta}) \tilde{\phi}_{\alpha\beta}^{-1} = \xi_{\alpha\beta}$. Here, using $\mathfrak{g} = \mathfrak{gl}_{l}(\mathbb{C})$, we identify the three sheaves $\operatorname{Hom}_{\mathcal{O}_{M}}(\mathbf{M}_{\mathbf{W}}, \mathbf{M}_{\mathbf{W}} \otimes_{\mathcal{O}_{M}} \mathcal{G}^{*}\mathbf{M})$, $\operatorname{Hom}_{\mathcal{O}_{M}}(\mathcal{G}\mathbf{M}, \mathbf{M}_{\mathfrak{g}})$, and $\mathbf{M}_{\mathfrak{g}} \otimes_{\mathcal{O}_{M}} \mathcal{G}^{*}\mathbf{M}$ via their respective canonical \mathcal{O}_{M} -module isomorphisms where $\mathcal{G}\mathbf{M}$, $\mathbf{M}_{\mathfrak{g}}$ are as in the equations (5.3) and (5.13) respectively.

Now, $\operatorname{Hom}_{\mathcal{O}_M}(\mathbf{E}, \mathbf{E} \otimes_{\mathcal{O}_M} \mathcal{G}^*\mathbf{M})$ is isomorphic to $\operatorname{Ad}(\mathbf{P}) \otimes_{\mathcal{O}_M} \mathcal{G}^*\mathbf{M}$ by Proposition 6.2. Therefore, upon identifying $\operatorname{Hom}_{\mathcal{O}_M}(\mathcal{G}\mathbf{M}, \operatorname{Ad}(\mathbf{P}))$, $\operatorname{Ad}(\mathbf{P}) \otimes_{\mathcal{O}_M} \mathcal{G}^*\mathbf{M}$, and also $\operatorname{Hom}_{\mathcal{O}_M}(\mathbf{E}, \mathbf{E} \otimes_{\mathcal{O}_M} \mathcal{G}^*\mathbf{M})$ via canonical \mathcal{O}_M -module isomorphisms, we have, via equations (5.15) and (6.15), that

 b_{c}

$$a_{lphaeta} = -a_{lphaeta}$$
 .

It follows that a(P) = -b(E).

7. Generalized complex structure and orbifold

Let M be a regular GC manifold of dimension 2m and type k. Let \mathscr{S} denote the associated symplectic foliation of complex codimension k which is transversely holomorphic. Let $T\mathscr{S}$ be the corresponding involutive subbundle of TM of rank 2m-2k, called the tangent bundle of the foliation. The normal bundle of the foliation, denoted by \mathcal{N} , is defined by

$$\mathcal{N} := TM/T\mathscr{S}.$$

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By [15, Proposition 4.2], \mathcal{N} is an integrable subbundle with a complex structure. Then \mathcal{N} has a decomposition given by the complex structure

$$\mathcal{N} \otimes \mathbb{C} = \mathcal{N}^{1,0} \oplus \mathcal{N}^{0,1} \,. \tag{7.1}$$

As the exact sequence

$$0 \longrightarrow T\mathscr{S} \longrightarrow TM \longrightarrow \mathcal{N} \longrightarrow 0$$

splits smoothly, \mathcal{N} may be regarded as a subbundle of TM complementary to $T\mathscr{S}$, and we may identify $\mathcal{N}^{1,0}$ with $\mathcal{G}M$. Define

$$\mathscr{M} := M/\mathscr{S} \tag{7.2}$$

to be the leaf space of the foliation \mathscr{S} . This is a topological space that has the quotient topology induced by the quotient map

$$\tilde{\pi}: M \longrightarrow \mathscr{M}$$
. (7.3)

The map $\tilde{\pi}$ is open (cf. [24, Section 2.4]).

In general, \mathscr{M} could be rather wild. To have a reasonable theory, we assume that \mathscr{M} admits a smooth orbifold structure. Since \mathscr{S} is transversely holomorphic, \mathscr{M} then becomes a complex orbifold. Moreover, observe that $\tilde{\pi}$ is a smooth complete orbifold map (cf. [5, Definition 3.1]): Namely, for any point $x \in M$ and $\tilde{\pi}(x) \in \mathscr{M}$, there exist orbifold charts \tilde{U} and $(\tilde{V}, \Gamma_{\tilde{\pi}(x)})$ corresponding to x and $\tilde{\pi}(x)$, respectively, such that the following diagram commutes.



Here $\Gamma_{\tilde{\pi}(x)}$ is the isotropy group corresponding to $\tilde{\pi}(x)$. The rows of the commutative diagram are diffeomorphisms of smooth orbifolds and $\tilde{\pi}$ is the lift of $\tilde{\pi}$. One can see from this diagram that each point $y \in \mathcal{M}$ is a regular value of $\tilde{\pi}$. Thus, by the preimage theorem for orbifolds (cf. [5, Theorem 4.2]), $\tilde{\pi}^{-1}(y)$ is an embedded submanifold of real dimension 2m - 2k for all $y \in \mathcal{M}$. Hence, each leaf is not only an immersed but also a closed embedded submanifold of M.

Definition 7.1. An open set in M is called a transverse open set if it is a union of leaves. An open cover $\mathcal{U} = \{U_{\alpha}\}$ is called a transverse open cover of M if each U_{α} is a transverse open subset of M.

Let S be a leaf of \mathscr{S} . By the Tubular Neighborhood Theorem, there exists a transverse neighborhood (tubular neighborhood) of S which is diffeomorphic to the normal bundle \mathcal{N}_S of S. One can see that \mathcal{N}_S is just the pullback of \mathcal{N} via the inclusion map $S \hookrightarrow M$. Due to the transverse complex structure, \mathcal{N} , as well as \mathcal{N}_S , can be thought of as a complex vector bundle of complex rank k. Consider the partial connection, known as the Bott connection (cf. [6, Section 6]), on \mathcal{N} which is flat along the leaves. Then its pullback on \mathcal{N}_S gives a flat connection. Thus, considering \mathcal{N}_S as a complex vector bundle, by [19, Proposition 1.2.5]

$$\mathcal{N}_S \cong \tilde{S} \times_o \mathbb{C}^k$$

where $\rho : \pi_1(S) \longrightarrow GL_k(\mathbb{C})$ is the linear holonomy representation of $\pi_1(S)$ and \tilde{S} is the universal cover of S.

Definition 7.2. A 2k-dimensional embedded submanifold of M is called a transversal section if it is transversal to the leaves of \mathscr{S} .

Note that by [24, Proposition 2.20], \mathscr{M} admits a Riemannian metric which makes \mathscr{S} into a Riemannian foliation. Since S is an embedded submanifold, $T \cap S$ is discrete for any transversal section T. Then, following the proof of [24, Theorem 2.6], one can show that the holonomy group of S, $\operatorname{Hol}(S)$ is finite. By the differentiable slice theorem, we can indeed assume that the action of $\operatorname{Hol}(S)$ on T is linear, that is,

$$\operatorname{Hol}(S) = \operatorname{img}(\rho)$$
.

We summarise our observations as follows.

Theorem 7.3. Let M be a regular GC manifold and let \mathscr{S} be the induced symplectic foliation. Assume that M/\mathscr{S} has a smooth orbifold structure. Then, we have the following.

- (1) Each leaf of \mathscr{S} is an embedded closed submanifold of M.
- (2) The holonomy group of each leaf is finite.
- (3) (M, \mathscr{S}) is a regular Riemannian foliation.
- (4) Around each leaf S, there exists a tubular neighborhood U such that U is diffeomorphic to S̃ ×_{Hol(S)} ℂ^k where S̃ is the universal cover of S and Hol(S) is the holonomy group of S. Here, Hol(S) acts on ℂ^k via a linear holonomy representation.

Example 7.4. Let F be a symplectic manifold and \tilde{F} be its universal cover. Then as in Example 3.13, $\tilde{F} \times_{\rho} \mathbb{C}^{l}$ is as regular GC manifold of type l. The induced symplectic

$$S_x = \left\{ [\tilde{m}, y] \mid \tilde{m} \in \tilde{F}, y \in [x] \right\} \quad \text{where} \quad [x] := \left\{ \rho(g) \cdot x \mid g \in \pi_1(F) \right\} \subset \mathbb{C}^l.$$

This implies that the leaf space $\tilde{F} \times_{\rho} \mathbb{C}^{l} / \mathscr{S}$ is exactly

$$\mathbb{C}^l/\rho := \{ [x] \mid x \in \mathbb{C}^l \}$$

The isotropy group at 0 is img ρ which is the linear holonomy group. Therefore, we get that $\tilde{F} \times_{\rho} \mathbb{C}^l / \mathscr{S}$ is a smooth orbifold if and only if the linear holonomy group is finite.

Remark 7.5. It is tempting to think that the leaf space of a regular GCS is either manifold or an orbifold. But, it may not be even Hausdorff. The following example demonstrates this.

Example 7.6. Consider the product GCS on $M \times F$ where M is a complex manifold and F is a symplectic manifold. Let $N \subset F$ be a closed submanifold such that $F \setminus N$ is disconnected. Fix $m \in M$, Consider the open submanifold

$$X_m = M \times F \setminus \{m \times N\}$$

Consider the natural regular GCS on X_m induced from $M \times F$. Let $(x, f) \in X_m$. Then, the leaf of the induced foliation \mathscr{S}_m , through (x, f), is of the following form

$$S_{(x,f)} = \begin{cases} F & \text{if } x \neq m, \\ (F \setminus N)_{\alpha} & \text{if } x = m, \end{cases}$$

where $(F \setminus N)_{\alpha}$ denotes the connected component of $F \setminus N$ that contains f for x = m. One can see that the leaf space X_m / \mathscr{S}_m is not Hausdroff. Thus, we obtain an infinite family of regular GC manifolds with non-Hausdorff leaf space.

8. Dolbeault cohomology of SGH vector bundles

8.1. Cohomolgy Theory

Let (M, \mathcal{J}_M) be a regular GC manifold with *i*-eigen bundle *L*. Then, $(TM \oplus T^*M) \otimes \mathbb{C} = L \oplus \overline{L}$. We have a differential operator,

$$d_L: C^{\infty}(\wedge^{\bullet}L^*) \longrightarrow C^{\infty}(\wedge^{\bullet+1}L^*), \qquad (8.1)$$

defined as follows. For any $\omega \in C^{\infty}(\wedge^n L^*)$ and $X_i \in C^{\infty}(L)$ for all $i \in \{1, \dots, n+1\}$,

$$d_L \omega(X_1, \cdots, X_{n+1}) := \sum_{i=1}^{n+1} (-1)^{i+1} \rho(X_i) (\omega(X_1, \cdots, \hat{X}_i, \cdots, X_{n+1})) + \sum_{i < j} (-1)^{i+j} \omega([X_i, X_j], X_1, \cdots, \hat{X}_i, \cdots, \cdots, \hat{X}_j, \cdots, X_{n+1}),$$

where $\rho : (TM \oplus T^*M) \otimes \mathbb{C} \longrightarrow TM \otimes \mathbb{C}$ is the projection map and [,] is the Courant bracket. Similarly, we have another operator

$$d_{\overline{L}}: C^{\infty}(\wedge^{\bullet}\overline{L}^*) \longrightarrow C^{\infty}(\wedge^{\bullet+1}\overline{L}^*).$$
(8.2)

Note that

$$\overline{\mathcal{G}^*M} = \overline{L} \cap (T^*M \otimes \mathbb{C}) \quad \text{and} \quad \overline{\mathcal{G}M} = (\overline{\mathcal{G}^*M})^*$$
(8.3)

are also smooth vector bundles over M (cf. (5.1), (5.3)). Let k be the type of \mathcal{J}_M . So, on a coordinate neighborhood U (cf. (2.10), Corollary 2.18),

$$C^{\infty}(\overline{\mathcal{G}^*M}|_U) = \operatorname{Span}_{C^{\infty}(U)}\{d\overline{z_1}, \dots, d\overline{z_k}\} \text{ and } C^{\infty}(\overline{\mathcal{G}M}|_U) = \operatorname{Span}_{C^{\infty}(U)}\{\frac{\partial}{\partial \overline{z_1}}, \dots, \frac{\partial}{\partial \overline{z_k}}\}$$

Let \mathscr{S} denote the induced regular transversely holomorphic symplectic foliation of complex codimension k corresponding to \mathcal{J}_M . Let $d_{\mathscr{S}}$ denote the exterior derivative along the leaves. Define

$$F_M := \ker(d_{\mathscr{S}} : C^{\infty}_M \longrightarrow C^{\infty}(T^*\mathscr{S} \otimes \mathbb{C}))$$

as the sheaf of smooth \mathbb{C} -valued functions over M which are constant along the leaves. Note that $\mathcal{O}_M \leq F_M \leq C_M^{\infty}$. For any vector bundle E over M whose transition maps are leaf-wise constant, we denote the sheaf of smooth leaf-wise constant sections of Eby $F_M(E)$.

The transition functions of \mathcal{G}^*M and $\overline{\mathcal{G}^*M}$ are constant along the leaves of \mathscr{S} . On a coordinate neighborhood U (cf. (2.10)),

$$F_M(\overline{\mathcal{G}^*M}|_U) = \operatorname{Span}_{F_M(U)} \{ d\overline{z_1}, \dots, d\overline{z_k} \},\$$

and

$$F_M(\overline{\mathcal{G}M}|_U) = \operatorname{Span}_{F_M(U)}\left\{\frac{\partial}{\partial \overline{z_1}}, \dots, \frac{\partial}{\partial \overline{z_k}}\right\}.$$

For any $p, q \ge 0$, define

$$\widetilde{A}^{p,q} := C^{\infty}(\wedge^{p}\mathcal{G}^{*}M \otimes \wedge^{q}\overline{\mathcal{G}^{*}M}),
A^{p,q} := F_{M}(\wedge^{p}\mathcal{G}^{*}M \otimes \wedge^{q}\overline{\mathcal{G}^{*}M}).$$
(8.4)

More specifically, given any open set $U \subseteq M$,

$$\widetilde{A}^{p,q}(U) = C^{\infty}(U, \wedge^{p}\mathcal{G}^{*}M) \otimes_{C^{\infty}(U)} C^{\infty}(U, \wedge^{q}\overline{\mathcal{G}^{*}M}),$$

$$A^{p,q}(U) = F_{M}(\wedge^{p}\mathcal{G}^{*}M)(U) \otimes_{F_{M}(U)} F_{M}(\wedge^{q}\overline{\mathcal{G}^{*}M})(U).$$
(8.5)

Note that $A^{p,q} \leq \tilde{A}^{p,q}$ and $\tilde{A}^{p,q} = A^{p,q} \otimes_{F_M} C_M^{\infty}$. For any $l \in \{0, \ldots, 2k\}$, denote $A^l = \bigoplus_{p+q=l} A^{p,q}$ and $\tilde{A}^l = \bigoplus_{p+q=l} \tilde{A}^{p,q}$. Thus, we get two bigraded sheaves, namely,

$$A := \bigoplus_{p,q} A^{p,q} \quad , \quad \tilde{A} := \bigoplus_{p,q} \tilde{A}^{p,q} \,. \tag{8.6}$$

To summarize, \tilde{A} and A are the bigraded sheaves of germs of sections of $\bigoplus_{p,q} (\wedge^p \mathcal{G}^* M \otimes \wedge^q \overline{\mathcal{G}^* M})$, which are smooth and constant along the leaves, respectively.
Let $d: C^{\infty}(\wedge^{\bullet}T^*M \otimes \mathbb{C}) \longrightarrow C^{\infty}(\wedge^{\bullet+1}T^*M \otimes \mathbb{C})$ be the exterior derivative. By [15, Proposition 4.2], we can see that $\mathcal{G}M$ and $\overline{\mathcal{G}M}$ both are integrable smooth sub-bundle of $TM \otimes \mathbb{C}$. Thus we can restrict d to \tilde{A}^{\bullet} , A^{\bullet} . We denote these restrictions by \tilde{D} and D, respectively, that is,

$$\dot{D} := d|_{\tilde{A}^{\bullet}} \quad , \quad D := d|_{A^{\bullet}} \,. \tag{8.7}$$

In particular, any $\omega \in A^{p,q}$ (respectively, $\tilde{A}^{p,q}$), is locally (cf. (2.10)) of the form

$$\omega = \sum_{I,J} f_{IJ} \, dz_I \wedge d\overline{z_J} \,,$$

where $f_{IJ} \in F_M(U)$ (respectively, $C^{\infty}(U)$), I, J are ordered subsets of $\{1, \ldots, k\}$, and $dz_I = \bigwedge_{i \in I} dz_i, d\overline{z_J} = \bigwedge_{j \in J} d\overline{z_j}$. Then,

$$D\omega \text{ (respectively, } \tilde{D}\omega) = \sum_{I,J} \partial f_{IJ} \, dz_I \wedge d\overline{z_J} + \sum_{I,J} \overline{\partial} f_{IJ} \, dz_I \wedge d\overline{z_J} \,, \qquad (8.8)$$

where ∂f_{IJ} and $\overline{\partial} f_{IJ}$ are defined by

$$\partial f_{IJ} := \sum_{i=1}^{k} \frac{\partial f_{IJ}}{\partial z_i} dz_i , \quad \overline{\partial} f_{IJ} := \sum_{i=1}^{k} \frac{\overline{\partial} f_{IJ}}{\partial \overline{z_i}} d\overline{z_i} . \tag{8.9}$$

We identify L^* with \overline{L} via the symmetric bilinear form defined in (2.1), and consider the restrictions of d_L to $C^{\infty}(\wedge^{\bullet}\overline{\mathcal{G}^*M})$ and and $d_{\overline{L}} C^{\infty}(\wedge^{\bullet}\mathcal{G}^*M)$. We denote these by \tilde{d}_L and $\tilde{d}_{\overline{L}}$, respectively. In particular, for any $\omega \in C^{\infty}(\wedge^p \mathcal{G}^*M)$, locally we can write

$$\omega = \sum_{I} f_{I} \, dz_{I} \, .$$

Then,

$$\tilde{d}_{\overline{L}}\omega = \sum_{I} d_{\overline{L}} f_{I}|_{C^{\infty}(\mathcal{G}^{*}M)} dz_{I}$$

We know that, for any $f \in C^{\infty}(U)$, $d_{\overline{L}}f \in L$ and $d_L f \in \overline{L}$. Therefore, if we restrict them to $C^{\infty}(\mathcal{G}^*M)$ and $C^{\infty}(\overline{\mathcal{G}^*M})$, respectively, we get that

$$d_{\overline{L}}|_{C^{\infty}(\mathcal{G}^*M)}f = \partial f , \quad d_L|_{C^{\infty}(\overline{\mathcal{G}^*M})}f = \overline{\partial}f ,$$

where ∂f and $\overline{\partial} f$ are defined as in (8.9). We can further restrict d_L and $d_{\overline{L}}$ to $F_M(\wedge^{\bullet}\overline{\mathcal{G}^*M})$ and $F_M(\wedge^{\bullet}\mathcal{G}^*M)$ which we again denote by d_L and $d_{\overline{L}}$, respectively. Thus we can consider the following morphisms of sheaves

$$d_L: F_M(\wedge^{\bullet}\overline{\mathcal{G}^*M}) \longrightarrow F_M(\wedge^{\bullet+1}\overline{\mathcal{G}^*M}), d_{\overline{L}}: F_M(\wedge^{\bullet}\mathcal{G}^*M) \longrightarrow F_M(\wedge^{\bullet+1}\mathcal{G}^*M).$$
(8.10)

Note that $d_L = \tilde{d}_L|_{F_M(\wedge^{\bullet}\overline{\mathcal{G}^*M})}$ and $d_{\overline{L}} = \tilde{d}_{\overline{L}}|_{F_M(\wedge^{\bullet}\mathcal{G}^*M)}$. They induce two differential complexes, namely $(F_M(\wedge^{\bullet}\overline{\mathcal{G}^*M}), d_L)$ and $(F_M(\wedge^{\bullet}\mathcal{G}^*M), d_{\overline{L}})$. Subsequently, we can naturally extend d_L and $d_{\overline{L}}$ to $A^{\bullet,\bullet}$, again denoted by d_L and $d_{\overline{L}}$ respectively, and get the

following morphisms of sheaves

$$d_L : A^{\bullet, \bullet} \longrightarrow A^{\bullet, \bullet+1};$$

$$d_{\overline{L}} : A^{\bullet, \bullet} \longrightarrow A^{\bullet+1, \bullet}.$$
(8.11)

In particular, for any $\omega \in A^{p,q}$, locally

$$\omega = \sum_{I,J} f_{IJ} \, dz_I \wedge d\overline{z_J} \, .$$

Then,

$$d_L\omega = \sum_J d_L f_{IJ}|_{F_M(\overline{\mathcal{G}^*M})} \wedge dz_I \wedge d\overline{z_J}, \quad d_{\overline{L}}\omega = \sum_I d_{\overline{L}} f_{IJ}|_{F_M(\mathcal{G}^*M)} \wedge dz_I \wedge d\overline{z_J}.$$
(8.12)

By the equations (8.8) and (8.12), on $A^{\bullet,\bullet}$, we have

$$D = d_{\overline{L}} + d_L$$
 and $D(A^{\bullet, \bullet}) \subseteq A^{\bullet + 1, \bullet} \oplus A^{\bullet, \bullet + 1}$

Similarly, one can see that $\tilde{D} = \tilde{d}_{\overline{L}} + \tilde{d}_{\overline{L}}$ where $\tilde{d}_{\overline{L}}$ and \tilde{d}_{L} are considered as a morphism of sheaves between $\tilde{A}^{\bullet,\bullet}$ to $\tilde{A}^{\bullet,\bullet+1,\bullet}$ and $\tilde{A}^{\bullet,\bullet+1}$, respectively.

Definition 8.1. Any element $\omega \in \tilde{A}^l$ is called a generalized form of order l and any element in $\tilde{A}^{p,q}$ is called a generalized form of type (p,q). Here $\tilde{A}^{p,q}$, \tilde{A}^l are as in (8.6).

Definition 8.2. Any element $\omega \in A^l$ is called a transverse generalized form of degree l and any element in $A^{p,q}$ is called a transverse generalized form of type (p,q). Here $A^{p,q}, A^l$ are as in (8.6).

Let $Z^{\bullet} = \ker(D : A^{\bullet} \longrightarrow A^{\bullet+1})$, i.e., the set of *D*-closed transverse generalized forms of degree *l*. Let $B^{\bullet}(M) = \operatorname{img}(D : A^{\bullet-1}(M) \longrightarrow A^{\bullet}(M))$, i.e., the set of *D*-exact transverse generalized forms of degree *l*. Then, the homology of the cochain complex $\{A^{\bullet}(M), D\}$ is called the *D*-cohomology of *M*, and it is denoted by

$$H_D^{\bullet}(M) := \frac{Z^{\bullet}(M)}{B^{\bullet}(M)} = \frac{\ker(D : A^{\bullet}(M) \longrightarrow A^{\bullet+1})(M)}{\operatorname{img}(D : A^{\bullet-1}(M) \longrightarrow A^{\bullet}(M))}.$$
(8.13)

Definition 8.3. Let $(\mathcal{G}^*\mathbf{M})^p := \bigwedge_{\mathcal{O}_M}^p \mathcal{G}^*\mathbf{M}$ for $p \in \mathbb{N}$ and $(\mathcal{G}^*\mathbf{M})^0 := \mathcal{O}_M$. Note that $(\mathcal{G}^*\mathbf{M})^{\bullet} < F_M(\wedge^{\bullet}\mathcal{G}^*M)$. We say that a transverse generalized form ω of type (p, 0) is a GH *p*-form if $d_L\omega = 0$, that is, $\omega \in (\mathcal{G}^*\mathbf{M})^p$.

Let N be another regular GC manifold and let $f:M\longrightarrow N$ be a GH map. Then it follows that

- (1) $f^*(A_N^{\bullet,\bullet}) \subset A_M^{\bullet,\bullet}$,
- $(2) f^* \circ d_{L_N} = d_{L_M} \circ f^*.$

Corollary 8.4. Let M be a GC manifold. Given an open set $U \subseteq M$, a smooth map $\psi : (U, \mathcal{J}_U) \longrightarrow \mathbb{C}$ is a GH function, that is, $f \in \mathcal{O}_M(U)$, if and only if $d_L f = 0$ where d_L as defined in (8.1).

Proof. Follows from Lemma 2.12.

Let $Z^{\bullet,\bullet} = \ker(d_L : A^{\bullet,\bullet} \longrightarrow A^{\bullet,\bullet+1})$ and let $B^{\bullet,\bullet}(M) = \operatorname{img}(d_L : A^{\bullet,\bullet-1}(M) \longrightarrow A^{\bullet,\bullet}(M))$. Then the homology of the cochain complex $\{A^{\bullet,\bullet}(M), d_L\}$ is called d_L -cohomology of M and it is denoted by

$$H_{d_L}^{\bullet,\bullet}(M) := \frac{Z^{\bullet,\bullet}(M)}{B^{\bullet,\bullet}(M)} = \frac{\ker(d_L : A^{\bullet,\bullet}(M) \longrightarrow A^{\bullet,\bullet+1})(M)}{\operatorname{img}(d_L : A^{\bullet,\bullet-1}(M) \longrightarrow A^{\bullet,\bullet}(M))}.$$
(8.14)

One can also consider the homology of the cochain complex $\{\tilde{A}^{\bullet}(M), \tilde{D}\}$ which is called the \tilde{D} -cohomology of M, and is denoted by

$$H^{\bullet}_{\tilde{D}}(M) := \frac{\ker(\tilde{D}: \tilde{A}^{\bullet}(M) \longrightarrow \tilde{A}^{\bullet+1})(M)}{\operatorname{img}(\tilde{D}: \tilde{A}^{\bullet-1}(M) \longrightarrow \tilde{A}^{\bullet}(M))}.$$

Similarly, the homology of the cochain complex $\{\tilde{A}^{\bullet,\bullet}(M), \tilde{d}_L\}$ which will be called \tilde{d}_L cohomology of M, and denoted by

$$H^{\bullet,\bullet}_{\tilde{d}_L}(M) := \frac{\ker(\tilde{d}_L : \tilde{A}^{\bullet,\bullet}(M) \longrightarrow \tilde{A}^{\bullet,\bullet+1})(M)}{\operatorname{img}(\tilde{d}_L : \tilde{A}^{\bullet,\bullet-1}(M) \longrightarrow \tilde{A}^{\bullet,\bullet}(M))}$$

We know that locally (cf. (2.10)),

$$C^{\infty}(\overline{\mathcal{G}^*M}|_U) = \operatorname{Span}_{C^{\infty}(U)}\{d\overline{z_1}, \dots, d\overline{z_k}\}$$

and

$$C^{\infty}(\mathcal{G}^*M|_U) = \operatorname{Span}_{C^{\infty}(U)} \{ dz_1, \dots, dz_k \},$$

where k is the type of M. Then, by following [13, P-25, P-42], one immediately obtains the result below.

Proposition 8.5. Let M be a regular GC manifold of type k. Then for any q > 0,

(1) \tilde{d}_L -Poincaré Lemma: For sufficiently small open set $U \subset M$, $H^{\bullet,q}_{\tilde{d}_I}(U) = 0$.

(2) $H^q(M, \tilde{A}^{\bullet, \bullet}) = 0$.

(3) \tilde{D} -Poincaré Lemma: For a sufficiently small open set $U \subset M$, $H^q_{\tilde{D}}(U) = 0$.

(4) $H^q(M, \tilde{A}^{\bullet}) = 0$.

Definition 8.6. An open cover $\mathcal{U} = \{U_{\alpha}\}$ of M is called a transverse good cover if \mathcal{U} is a locally finite transverse open cover (cf. Definition 7.1) and any finite intersection $\bigcap_{i=0}^{l} U_{\alpha_i}$ is diffeomorphic to a tubular neighborhood as in Theorem 7.3.

Proposition 8.7. Let M be a regular GC manifold of type k. Assume M/\mathscr{S} has a smooth orbifold structure. Let $\mathcal{U} = \{U_{\alpha}\}$ be a sufficiently fine transverse good cover of M. Then for any q > 0,

(1) d_L -Poincaré Lemma: For a sufficiently small transverse open set $U \subset M$,

$$H^{\bullet,q}_{d_L}(U) = 0$$

(2) D-Poincaré Lemma: For a sufficiently small transverse open set $U \subset M$,

$$H_D^q(U) = 0$$

- (3) $H^q(\mathcal{U}, A^{\bullet, \bullet}) = 0$.
- $(4) H^q(\mathcal{U}, A^\bullet) = 0.$

Proof. By Theorem 7.3, there exists a transverse open set (tubular neighborhood) U around a leaf S which is diffeomorphic to $\tilde{S} \times_{\operatorname{Hol}(S)} \mathbb{C}^k$ where \tilde{S} is the universal cover of S and $\operatorname{Hol}(S)$ is the holonomy group of S. Since $\operatorname{Hol}(S)$ is finite, it acts linearly. Recall that $\mathcal{N}^* \otimes \mathbb{C} = \mathcal{G}^* M \oplus \overline{\mathcal{G}^* M}$ where \mathcal{N} is the normal bundle of \mathscr{S} . Taking U to be sufficiently small, we have

$$F_M(\overline{\mathcal{G}^*M}|_U) = \operatorname{Span}_{F_M(U)} \{ d\overline{z_1}, \dots, d\overline{z_k} \},\$$

and

$$F_M(\mathcal{G}^*M|_U) = \operatorname{Span}_{F_M(U)} \{ dz_1, \dots, dz_k \}$$

Then following the proof in [13, P-25, P-42], we can prove (1) and (2).

To prove (3) and (4), it is enough to show that there is a partition of unity subordinate to \mathcal{U} such that they are constant along the leaves. This is obtained easily by pulling back a partition of unity for M/\mathscr{S} subordinate to $\hat{\mathcal{U}} = (\tilde{\pi}(U_{\alpha}))$ with respect to the quotient map $\tilde{\pi} : M \longrightarrow M/\mathscr{S}$. \Box

Proposition 8.8. (de Rham cohomology for regular GC manifold) Let M be a regular GC manifold with induced symplectic foliation \mathscr{S} . Assume the leaf space M/\mathscr{S} admits a smooth orbifold structure. Then for $q \geq 0$,

$$H^q(\mathcal{U}, \{\mathbb{C}\}) \cong H^q_D(M),$$

where $\{\mathbb{C}\}\$ is the sheaf of locally constant \mathbb{C} -valued functions and \mathcal{U} is a sufficiently fine transverse good cover of M.

Proof. By *D*-Poincaré Lemma, we have the following exact sequence of sheaves

$$0 \longrightarrow \{\mathbb{C}\} \longleftrightarrow A^0 \xrightarrow{D} A^1 \xrightarrow{D} \cdots$$
(8.15)

on M. This gives the following exact sequence,

$$0 \longrightarrow Z^{\bullet} \longmapsto A^{\bullet} \xrightarrow{D} Z^{\bullet+1} \longrightarrow 0.$$
(8.16)

In particular, the sequence

$$0 \longrightarrow \{\mathbb{C}\} \longleftrightarrow A^0 \xrightarrow{D} Z^1 \longrightarrow 0$$
(8.17)

is exact. By (4) in Proposition 8.7, $H^q(\mathcal{U}, A^{\bullet}) = 0$ for all q > 0. Thus, considering the associated long exact sequences in cohomology for these exact sequences of sheaves, as in [13, pp. 40-41, 44], we obtain that for all $q \ge 0$

$$H^{q}(\mathcal{U}, \{\mathbb{C}\}) \cong H^{q-1}(\mathcal{U}, Z^{1}) \quad (by \ (8.17))$$
$$\cong H^{q-2}(\mathcal{U}, Z^{2}) \quad (by \ (8.16))$$
$$\vdots$$
$$\cong H^{1}(\mathcal{U}, Z^{q-1}) \quad (by \ (8.16))$$
$$\cong \frac{H^{0}(\mathcal{U}, Z^{q})}{D(H^{0}(\mathcal{U}, Z^{q-1}))}$$
$$= \frac{Z^{q}(M)}{B^{q}(M)} = H^{q}_{D}(M) .$$

Theorem 8.9. Let M be a regular GC manifold with induced symplectic foliation \mathscr{S} . Assume that the leaf space M/\mathscr{S} admits an orbifold structure. Then for any $p, q \ge 0$,

$$H^q(M, (\mathcal{G}^*\mathbf{M})^p) \cong H^{p,q}_{d_L}(M).$$

Proof. By d_L -Poincaré Lemma, the following sequences of sheaves,

$$0 \longrightarrow (\mathcal{G}^* \mathbf{M})^{\bullet} \longleftrightarrow A^{\bullet,0} \xrightarrow{d_L} Z^{\bullet,1} \longrightarrow 0, \qquad (8.18)$$

$$0 \longrightarrow Z^{\bullet,\bullet} \longleftrightarrow A^{\bullet,\bullet} \xrightarrow{d_L} Z^{\bullet,\bullet+1} \longrightarrow 0$$
(8.19)

are exact. Let \mathcal{U} be a sufficiently fine transverse good cover of M. By (3) in Proposition 8.7, $H^r(\mathcal{U}, A^{\bullet, \bullet}) = 0$ for all r > 0. Hence, using the long exact sequences in cohomology

associated with (8.18) and (8.19) (cf. [13, pp. 40-41]), we have,

$$H^{q}(\mathcal{U}, (\mathcal{G}^{*}\mathbf{M})^{p}) \cong H^{q-1}(\mathcal{U}, Z^{p,1}) \quad (by \ (8.18))$$
$$\cong H^{q-2}(\mathcal{U}, Z^{p,2}) \quad (by \ (8.19))$$
$$\cong H^{q-3}(\mathcal{U}, Z^{p,3}) \quad (by \ (8.19))$$
$$\vdots$$
$$\cong H^{1}(\mathcal{U}, Z^{p,q-1}) \quad (by \ (8.19))$$
$$\cong \frac{H^{0}(\mathcal{U}, Z^{p,q})}{d_{L}(H^{0}(\mathcal{U}, Z^{p,q-1}))}$$
$$= \frac{Z^{p,q}(M)}{B^{p,q}(M)} = H^{p,q}_{d_{L}}(M).$$

We can choose $\mathcal{U} = \{U_{\alpha}\}$ such that any finite intersection $V = \bigcap_{i=0}^{l} U_{\alpha_{i}}$ is diffeomorphic a tubular neighborhood as in Theorem 7.3. Fix such a V. Then $\mathcal{V} := \{V \cap U_{\alpha}\}$ is a transverse good cover of V. Note that $H^{q}(V, A^{\bullet, \bullet}) = 0$. Then, as above,

$$H^q(\mathcal{V}, (\mathcal{G}^*\mathbf{M})^p|_V) = H^{p,q}_{d_L}(V).$$

Since $H^{p,q}_{d_L}(W) = 0$ for any finite intersection W of elements in \mathcal{V} by the d_L -Poincaré Lemma, using Leray's theorem we have,

$$H^q(V, (\mathcal{G}^*\mathbf{M})^p|_V) = H^q(\mathcal{V}, (\mathcal{G}^*\mathbf{M})^p|_V) = H^{p,q}_{d_L}(V) \,.$$

Again, by the d_L -Poincaré Lemma, $H_{d_L}^{p,q}(V) = 0$. Thus, by Leray's Theorem, for all $p, q \ge 0$,

$$H^q(\mathcal{U}, (\mathcal{G}^*\mathbf{M})^p) \cong H^q(M, (\mathcal{G}^*\mathbf{M})^p).$$

Let E be an SGH vector bundle over M. We put

$$A_E := A \otimes_{\mathcal{O}_M} \mathbf{E} \,, \tag{8.20}$$

where A is as in (8.6). Since A is an F_M -module, it is also \mathcal{O}_M -module, and thus, A_E is well-defined. We can extend d_L from A to A_E , denoted by d'_L , as follows: For $f \in F_M$, $\alpha \in A$ and $\beta \in \mathbf{E}$, we can define $d'_L(f\alpha \wedge \beta) = fd_L(\alpha) \wedge \beta$. This definition is well-defined because if $f \in \mathcal{O}_M$, we have $f\alpha \wedge \beta = \alpha \wedge f\beta$. Then

$$egin{aligned} ec{d}_L(flpha\wedgeeta) &= fd_Llpha\wedgeeta & (\mathrm{as}\ d_Lf=0) \ &= d_Llpha\wedge(feta) \ &= d_L'(lpha\wedge feta) \,. \end{aligned}$$

For notational convenience, we again denote by d_L the extension d'_L of the operator d_L . We denote the component of type (p,q) of the cohomology of the complex $(H^0(M, A_E), d_L)$ by $H^{p,q}_{d_L}(M, E)$. Note that tensoring the short exact sequences (8.18) and (8.19) with the locally free sheaf **E** again yields short exact sequences. Then, following the proof of Theorem 8.9, we get the following.

Corollary 8.10. $H^{p,q}_{d_L}(M, E) \cong H^q(M, (\mathcal{G}^*\mathbf{M})^p \otimes_{\mathcal{O}_M} \mathbf{E}).$

8.2. Cohomology class of the curvature

Let G be a complex Lie group with complex Lie algebra \mathfrak{g} . Let $G \hookrightarrow P \longrightarrow M$ be an SGH principal bundle. Then, by applying Corollary 8.10 to $\operatorname{Ad}(\mathbf{P})$ where Ad(P) is as in (5.11), we have the following.

Corollary 8.11. $H^q(M, (\mathcal{G}^*\mathbf{M})^p \otimes_{\mathcal{O}_M} \mathbf{Ad}(\mathbf{P})) \cong H^{p,q}_{d_L}(M, Ad(P)).$

Let $\Theta = \{\Theta_{\alpha}\} \in \tilde{A}^{1,0} \otimes_{\mathcal{O}_M} \mathbf{Ad}(\mathbf{P})$ be a smooth generalized connection on P (see Definition 5.7 and Section 5.3), where

$$\Theta_{\alpha} \in C^{\infty}(U_{\alpha}, \operatorname{Hom}_{C^{\infty}_{M}}(C^{\infty}(\mathcal{G}M), C^{\infty}(M_{\mathfrak{g}})))$$

on a trivializing neighborhood U_{α} of P. Then, the curvature of this smooth generalized connection is defined on U_{α} by

$$\Omega_{\alpha} := \tilde{D}\Theta_{\alpha} + \frac{1}{2}[\Theta_{\alpha}, \Theta_{\alpha}] \tag{8.21}$$

where Θ_{α} is considered as \mathfrak{g} valued function. Then, by using either of the equations (5.19) or (5.20), we get

$$\Omega_{\alpha} = \operatorname{Ad}(\phi_{\alpha\beta}) \,\Omega_{\beta} \quad \text{on } U_{\alpha} \cap U_{\beta} \,,$$

or
$$\Omega_{\beta} = \operatorname{Ad}(\phi_{\beta\alpha}) \,\Omega_{\alpha} \quad \text{on } U_{\alpha} \cap U_{\beta} \,.$$

(8.22)

So, after patching, we get an element $\Omega \in C^{\infty}(M, \wedge^2(\mathcal{G}M \oplus \overline{\mathcal{G}M})^*) \otimes Ad(P))$. Ω is called the curvature of the smooth generalized connection Θ .

Let $\Theta \in A^{1,0}_{Ad(P)}$ be such that $\Theta_{\alpha} \in A^{1,0}_{M_{\mathfrak{g}}}$ for every α . This type of connection always exists due to the existence of partition of unity on the orbifold leaf space M/\mathscr{S} . We can then reformulate equation (8.21) as

$$\Omega_{\alpha} = D\Theta_{\alpha} + \frac{1}{2}[\Theta_{\alpha}, \Theta_{\alpha}] \quad \text{on } U_{\alpha}.$$
(8.23)

This shows that the (1, 1) component of Ω_{α} , denoted by $\Omega_{\alpha}^{1,1}$, is given by

$$\Omega_{\alpha}^{1,1} = d_L \Theta_{\alpha} \quad \text{on } U_{\alpha} \,. \tag{8.24}$$

By (8.22), we have

$$\Omega_{\alpha}^{1,1} = \operatorname{Ad}(\phi_{\alpha\beta})\Omega_{\beta}^{1,1} \quad \text{on} \quad U_{\alpha} \cap U_{\beta} ,$$

or
$$\Omega_{\beta}^{1,1} = \operatorname{Ad}(\phi_{\beta\alpha})\Omega_{\alpha}^{1,1} \quad \text{on} \quad U_{\alpha} \cap U_{\beta} .$$
(8.25)

After patching, we get a global element $\Omega \in (F_M(\wedge^2(\mathcal{G}^*M \oplus \overline{\mathcal{G}^*M})) \otimes_{\mathcal{O}_M} \operatorname{Ad}(\mathbf{P}))(M)$ whose (1,1)-component is $\Omega^{1,1}$. Then from the equations (5.19), (5.20), (8.24) and (8.25), we can see that the d_L -cohomology class $[\Omega^{1,1}]$ of $\Omega^{1,1}$ is independent of the choice of a smooth generalized connection of type (1,0). Note that $[\Omega^{1,1}]$ maps to a(P), as defined in Theorem 5.5, via the isomorphism in Corollary 8.11. We summarise our results as follows.

Theorem 8.12. Let P be an SGH principal G-bundle over a regular GC manifold M where G is a complex Lie group. Assume that the leaf space of the induced symplectic foliation on M admits a smooth orbifold structure. Let Θ be a smooth generalized connection of type (1,0) on P, which is constant along the leaves. Let $\Omega^{1,1}$ denote the corresponding (1,1) component of the curvature. Let $[\Omega^{1,1}]$ be the d_L -cohomology class in $H^{1,1}_{d_L}(M, Ad(P))$. Then $[\Omega^{1,1}]$ corresponds to $a(P) \in H^1(M, \mathcal{G}^*\mathbf{M} \otimes_{\mathcal{O}_M} \mathbf{Ad}(\mathbf{P}))$ via the isomorphism in Corollary 8.11.

9. Generalized Chern-Weil Theory and characteristic class

Let $\operatorname{Sym}^k(\mathfrak{g}^*)$ denotes the set of all symmetric k-linear mappings $\mathfrak{g} \times \mathfrak{g} \times \cdots \times \mathfrak{g} \longrightarrow \mathbb{C}$ on the Lie algebra \mathfrak{g} . Define the right adjoint action of the Lie group G on $\operatorname{Sym}^k(\mathfrak{g}^*)$ by

$$(f,g) \mapsto \operatorname{Ad}(g^{-1})f$$

where $(\operatorname{Ad}(g^{-1})f)(x_1,\ldots,x_k) = f(\operatorname{Ad}(g^{-1})x_1,\ldots,\operatorname{Ad}(g^{-1})x_k)$ (9.1)

for any $f \in \text{Sym}^k(\mathfrak{g}^*)$ and $g \in G$. Denote the space of Ad(G)-invariant forms by

$$\operatorname{Sym}^{k}(\mathfrak{g}^{*})^{G} := \{ f \in \operatorname{Sym}^{k}(\mathfrak{g}^{*}) \mid \operatorname{Ad}(g^{-1})f = f \,\,\forall \,\, g \in G \}$$
(9.2)

Now, given any $f \in \text{Sym}^k(\mathfrak{g}^*)^G$, we define a 2k-form in A^{2k} , of type (k, k), by

$$f(\Omega^{1,1})(X_1, X_2..., X_{2k}) := \frac{1}{(2k)!} \sum_{\sigma} \epsilon_{\sigma} f(\Omega^{1,1}(X_{\sigma(1)}, X_{\sigma(2)}), \dots, \Omega^{1,1}(X_{\sigma(2k-1)}, X_{\sigma(2k)}))$$
(9.3)

for $X_1, \ldots, X_{2k} \in F_M(\mathcal{G}M \oplus \overline{\mathcal{G}M})$, where σ is an element of the symmetric group S_{2k} , ϵ_{σ} denotes the sign of the permutation $\sigma \in S_{2k}$, and $\Omega^{1,1}$ is defined as in Theorem 8.12.

Let $\mathbb{C}[\mathfrak{g}]$ be the algebra of \mathbb{C} -valued polynomials on \mathfrak{g} . Consider the same adjoint action of G on $\mathbb{C}[\mathfrak{g}]$ as in (9.1), and let $\mathbb{C}[\mathfrak{g}]^G$ denote the subalgebra of fixed points under this action. Then any $f \in \operatorname{Sym}^k(\mathfrak{g}^*)^G$ can be viewed as a homogeneous polynomial function of degree k in $\mathbb{C}[\mathfrak{g}]^G$ that is,

$$\operatorname{Sym}^k(\mathfrak{g}^*)^G < \mathbb{C}[\mathfrak{g}]^G \text{ for any } k \ge 0.$$

We set

$$\operatorname{Sym}(\mathfrak{g}^*)^G := \bigoplus_{k=0}^{\infty} \operatorname{Sym}^k(\mathfrak{g}^*)^G.$$

Then, $\operatorname{Sym}(\mathfrak{g}^*)^G$ can be viewed as a sub-algebra of $\mathbb{C}[\mathfrak{g}]^G$.

Since $d_L\Omega^{1,1} = 0$, we can see that $d_Lf(\Omega^{1,1}) = 0$ for any $f \in \text{Sym}^k(\mathfrak{g}^*)^G$. Thus $f(\Omega^{1,1}) \in H^{k,k}_{d_L}(M)$. We define a map

$$\Phi_k : \operatorname{Sym}^k(\mathfrak{g}^*)^G \longrightarrow H^{k,k}_{d_L}(M) ,$$

$$f \mapsto [f(\Omega^{1,1})] .$$
(9.4)

Using the algebra structure of $\text{Sym}(\mathfrak{g}^*)^G$, we extend the map in (9.4) to an algebra homomorphism

$$\Phi: \operatorname{Sym}(\mathfrak{g}^*)^G \longrightarrow H^*_{d_L}(M),$$

$$f \mapsto [f(\Omega^{1,1})],$$
(9.5)

where $H_{d_L}^*(M) := \bigoplus_{k,l} H_{d_L}^{k,l}(M)$. Note that $\operatorname{img} \Phi \subseteq \bigoplus_{k \ge 0} H_{d_L}^{k,k}(M)$. We show that Φ is independent of the choice of a smooth generalized connection of type (1,0) which is constant along the leaves. For that, consider two smooth generalized connections Θ , Θ' of type (1,0) on the SGH principal bundle P over M which are constant along the leaves. Define

$$\begin{split} \omega &= \Theta - \Theta'; \\ \omega_t &= \Theta' + t\omega, \text{ for } t \in [0, 1]. \end{split}$$

From the equations (5.19) and (5.20), one can see that ω_t is a 1-parameter family of smooth generalized connections of type (1,0) constant along the leaves. Let Ω_t be the curvature of ω_t and let $\Omega_t^{1,1}$ be the (1,1) component of Ω_t . By (8.24), we have

$$\Omega_t^{1,1} = d_L \omega_t ,$$

= $d_L \Theta' + t \, d_L \omega ,$
$$\implies \frac{d\Omega_t^{1,1}}{dt} = d_L \omega .$$
 (9.6)

Consider the transverse generalized (2k-1)-form of type (k, k-1), defined by

$$\varphi = k \int_0^1 f(\omega, \Omega_t^{1,1}, \dots, \Omega_t^{1,1}) \, dt \,.$$
(9.7)

Note that

$$k d_L f(\omega, \Omega_t^{1,1}, \dots, \Omega_t^{1,1}) = k f(d_L \omega, \Omega_t^{1,1}, \dots, \Omega_t^{1,1}),$$

= $k f(\frac{d\Omega_t^{1,1}}{dt}, \Omega_t^{1,1}, \dots, \Omega_t^{1,1})$ (by (9.6)), (9.8)
= $\frac{d}{dt} (f(\Omega_t^{1,1}, \dots, \Omega_t^{1,1})).$

Hence,

$$d_L \varphi = \int_0^1 \frac{d}{dt} (f(\Omega_t^{1,1}, \dots, \Omega_t^{1,1})) dt = f(\Omega_1^{1,1}, \dots, \Omega_1^{1,1}) - f(\Omega_0^{1,1}, \dots, \Omega_0^{1,1}).$$

This shows that the algebra homomorphism Φ , in (9.5), is independent of the choice of smooth generalized connections of type (1,0) which are constant along the leaves.

Definition 9.1. The algebra homomorphism Φ , defined in (9.5), is called the *generalized* Chern-Weil homomorphism.

9.1. Generalized Chern class

Let $P \longrightarrow M$ be an SGH principal *G*-bundle over a regular GC manifold *M*. Let *G* be a complex Lie group with a canonical faithful representation such as a classical complex Lie group. Then the complex Lie algebra \mathfrak{g} is identified with a complex subalgebra of $M_l(\mathbb{C})$ where *l* is the dimension of the representation. For any $A \in \mathfrak{g}$, consider the following characteristic polynomial

$$\det\left(I + t\frac{A}{2\pi i}\right) = \sum_{k=0}^{l} f_k(A) t^k, \qquad (9.9)$$

where $f_k \in \mathbb{C}[\mathfrak{g}]$ is an elementary symmetric polynomial of degree k and I is the identity matrix. Since the right hand side of (9.9) is invariant under $\mathrm{Ad}(G)$ -action, we have

$$f_k \in \operatorname{Sym}^k(\mathfrak{g}^*)^G$$
.

Following [28, Example 32.3], we define an analogue of Chern classes for an SGH principal G-bundles where G is a complex Lie group with a holomorphic faithful representation.

Definition 9.2. The k-th generalized Chern class of P, denoted by $\mathbf{g}_{c_k}(P)$, is defined as the image of f_k under the generalized Chern-Weil homomorphism, that is,

$$\mathbf{g}c_k(P) := \Phi(f_k)$$

where Φ as defined in (9.5).

Proposition 9.3. $\mathbf{g}c_1(P) = \left[\left(\frac{1}{2\pi i}\right) \operatorname{Trace}(\Omega^{1,1})\right]$, where $\Omega^{1,1}$ as defined in (8.24).

Proof. Consider the usual determinant map det : $M_l(\mathbb{C}) \longrightarrow \mathbb{C}$, and the smooth map $(\det \circ \psi)(z) = \sum_{k=0}^l f_k(A) z^k$, where $\psi(z) = I + z \frac{A}{2\pi i}$ for all $z \in \mathbb{C}$, $A \in \mathfrak{g}$. Here, \mathfrak{g} is identified with a complex subalgebra of $M_l(\mathbb{C})$. After differentiating both sides with respect to z, at z = 0, we get $f_1(A) = \left(\frac{\operatorname{Trace}(A)}{2\pi i}\right)$ which concludes the proof. \Box

10. Connection on SGH vector bundle

Let M be a regular GC manifold and E be an SGH vector bundle over M. Set

$$\tilde{A}_E := \tilde{A} \otimes_{C_M^{\infty}} C_M^{\infty}(E) = \tilde{A} \otimes_{\mathcal{O}_M} \mathbf{E} \,, \tag{10.1}$$

where \tilde{A} is defined in (8.6).

Definition 10.1. A smooth generalized connection on an SGH vector bundle E, is a \mathbb{C} -linear sheaf homomorphism

$$abla : \tilde{A}^0_E \longrightarrow \tilde{A}^1_E$$

which satisfies the Leibniz rule

$$\nabla(fs) = \tilde{D}f \otimes s + f\nabla(s)$$

for any local function on M and any local section s of E.

Let $\{U_{\alpha}, \phi_{\alpha}\}$ be a system of local trivializations of E. Then, on U_{α} , we may write

$$\nabla|_{U_{\alpha}} = \phi_{\alpha}^{-1} \circ (\tilde{D} + \theta_{\alpha}) \circ \phi_{\alpha}$$

where θ_{α} is a matrix valued generalized 1-form. On $U_{\alpha} \cap U_{\beta}$, we have

$$\begin{split} \phi_{\beta}^{-1} \circ (\tilde{D} + \theta_{\beta}) \circ \phi_{\beta} &= \phi_{\alpha}^{-1} \circ (\tilde{D} + \theta_{\alpha}) \circ \phi_{\alpha} \\ \Longrightarrow \phi_{\beta}^{-1} \circ \theta_{\beta} \circ \phi_{\beta} - \phi_{\alpha}^{-1} \circ \theta_{\alpha} \circ \phi_{\alpha} &= \phi_{\alpha}^{-1} \circ \tilde{D} \circ \phi_{\alpha} - \phi_{\beta}^{-1} \circ \tilde{D} \circ \phi_{\beta} \\ \Longrightarrow \begin{cases} \phi_{\beta}^{-1} \circ \theta_{\beta} \circ \phi_{\beta} - \phi_{\alpha}^{-1} \circ \theta_{\alpha} \circ \phi_{\alpha} &= \phi_{\beta}^{-1} \circ (\phi_{\alpha\beta}^{-1} \circ \tilde{D} \circ \phi_{\alpha\beta} - \tilde{D}) \circ \phi_{\beta} \\ \text{or} \\ \phi_{\beta}^{-1} \circ \theta_{\beta} \circ \phi_{\beta} - \phi_{\alpha}^{-1} \circ \theta_{\alpha} \circ \phi_{\alpha} &= \phi_{\alpha}^{-1} \circ (\tilde{D} - \phi_{\alpha\beta} \circ \tilde{D} \circ \phi_{\alpha\beta}^{-1}) \circ \phi_{\alpha} \end{split}$$

Thus, we get the following co-boundary equation for ∇ .

$$\begin{cases} \theta_{\beta} - \operatorname{Ad}(\phi_{\beta\alpha}) \cdot \theta_{\alpha} = \phi_{\alpha\beta}^{-1} \tilde{D}(\phi_{\alpha\beta}) \\ \text{or} & \text{on } U_{\alpha} \cap U_{\beta} . \\ \operatorname{Ad}(\phi_{\alpha\beta}) \cdot \theta_{\beta} - \theta_{\alpha} = -\phi_{\alpha\beta} \tilde{D}(\phi_{\alpha\beta}^{-1}) \end{cases}$$
(10.2)

A straightforward modification of the proof of [18, Proposition 4.2.3] yields the following.

Proposition 10.2. Let E be an SGH vector bundle over M. Then

- (1) For any two smooth generalized connections ∇, ∇' on an SGH vector bundle E, $\nabla \nabla'$ is \tilde{A}^0 -linear.
- (2) For any $\theta \in \tilde{A}^1_{\operatorname{End}(E)}(M)$, $\nabla + \theta$ is also a smooth generalized connection of E.
- (3) The set of all smooth generalized connections on E, is an affine space over the (infinite-dimensional) \mathbb{C} -vector space $\tilde{A}^1_{\operatorname{End}(E)}(M)$.

Any SGH vector bundle E is also a complex vector bundle and it admits a hermitian metric h. The pair (E, h) is then known as a hermitian vector bundle.

Definition 10.3. Given a hermitian vector bundle (E, h), a smooth generalized connection ∇ is called a generalized hermitian connection with respect to h if for any two local sections s, s', one has

$$\tilde{D}(h(s,s')) = h(\nabla s,s') + h(s,\nabla s').$$
(10.3)

Let θ be a element in $A^{1}_{\text{End}(E)}(M)$ and ∇ be a generalized hermitian connection. Then, by Proposition 10.2, $\nabla + \theta$ is also a smooth generalized connection. Now, one can see that $\nabla + \theta$ satisfies (10.3) if and only if $h(\theta s, s') + h(s, \theta s') = 0$ for all smooth local sections s, s'. Consider the subsheaf

$$\operatorname{End}(E,h) := \{ \theta \in C^{\infty}(\operatorname{End}(E)) \mid h(\theta s, s') + h(s, \theta s') = 0 \ \forall \ \text{local sections} \ s, s' \}$$

of $C^{\infty}(\operatorname{End}(E))$. Note that $\operatorname{End}(E,h)$ has the structure of a real vector bundle.

Proposition 10.4. The set of all generalized hermitian connections on (E, h) is an affine space over the (infinite-dimensional) \mathbb{R} -vector space $\tilde{A}^1_{\operatorname{End}(E,h)}(M)$ where $\tilde{A}^1_{\operatorname{End}(E,h)} = \tilde{A}^1 \otimes_{C^{\infty}_{M,\mathbb{R}}} C^{\infty}_{M,\mathbb{R}}(\operatorname{End}(E,h))$ and $C^{\infty}_{M,\mathbb{R}}$ is the sheaf of real valued smooth functions.

Proof. Follows from Proposition 10.2 after considering E as a real vector bundle. \Box

Remark 10.5. (cf. [18, Section 4.2]) $\operatorname{End}(E, h)$ is not always an SGH vector bundle. It is not even always a complex vector bundle. For example, if $E = M \times \mathbb{C}$ is the trivial SGH vector bundle. Then $\operatorname{End} E$ is again $M \times \mathbb{C}$ but $\operatorname{End}(E, h)$ is just the $M \times i\mathbb{R}$.

Now $\tilde{A}_E^1 = \tilde{A}_E^{1,0} + \tilde{A}_E^{0,1}$, as in (8.4). So, we can decompose any smooth generalized connection ∇ into two components, $\nabla^{1,0}$ and $\nabla^{0,1}$ such that $\nabla = \nabla^{1,0} + \nabla^{0,1}$ where

$$abla^{1,0}: \tilde{A}^0_E \longrightarrow \tilde{A}^{1,0}_E \quad ; \quad
abla^{0,1}: \tilde{A}^0_E \longrightarrow \tilde{A}^{0,1}_E .$$

Note that for any local function f on M and local section s of E,

$$\nabla^{0,1}(fs) = \tilde{d}_L f \otimes s + f \nabla^{0,1}(s) \,.$$

Definition 10.6. A smooth generalized connection ∇ on E is compatible with the GCS if $\nabla^{0,1} = \tilde{d}_L$.

After some straightforward modifications of the proofs in [18, Corollary 4.2.13, Proposition 4.2.14] one obtains the following.

Proposition 10.7. Let E be an SGH vector bundle over M with a hermitian structure h.

- (1) The space of smooth generalized connections on E, compatible with the GCS, forms an affine space over the \mathbb{C} -vector space $\tilde{A}^{1,0}_{\operatorname{End}(E)}(M)$.
- (2) There exists a unique generalized hermitian connection ∇ on E with respect to h which is also compatible with the GCS. This smooth generalized connection is called generalized Chern connection.

Definition 10.8. The curvature of a smooth generalized connection ∇ , denoted by Ω_{∇} and referred to as a smooth generalized curvature, is the composition

$$\Omega_{\nabla} := \nabla \circ \nabla : \tilde{A}^0_E \longrightarrow \tilde{A}^1_E \longrightarrow \tilde{A}^2_E.$$

Example 10.9. Let $E = M \times \mathbb{C}^l$ be the trivial SGH vector bundle. By Proposition 10.2, any smooth generalized connection is of the form $\nabla = \tilde{D} + \theta$ where $\theta \in \tilde{A}^1_{\text{End}(E)}(M)$. Note that $\tilde{D} : \tilde{A}^p \to \tilde{A}^{p+1}$ extends naturally to $\tilde{D} : \tilde{A}^p_E \to \tilde{A}^{p+1}_E$ by the Leibniz rule. So, for any local section $s \in \tilde{A}^0_E$, we have

$$\Omega_{\nabla}(s) = (D+\theta)(Ds+\theta s)$$

= $\tilde{D}(\tilde{D}s) + (\tilde{D}(\theta s) + \theta \wedge \tilde{D}s) + \theta \wedge \theta(s)$
= $(\theta \wedge \theta + \tilde{D}(\theta))(s)$.

For any smooth generalized connection ∇ on an SGH vector bundle E with local trivialization $\{U_{\alpha}, \phi_{\alpha}\}$, we know that $\nabla = \phi_{\alpha}^{-1} \circ (\tilde{D} + \theta_{\alpha}) \circ \phi_{\alpha}$. By (10.2), on $U_{\alpha\beta}$,

$$\theta_{\beta} = \operatorname{Ad}(\phi_{\beta\alpha}) \cdot \theta_{\alpha} + \phi_{\alpha\beta}^{-1} \tilde{D}(\phi_{\alpha\beta}).$$

This implies

$$\tilde{D}(\theta_{\beta}) = \tilde{D}(\phi_{\beta\alpha}) \wedge \tilde{D}(\phi_{\alpha\beta}) + \tilde{D}(\phi_{\beta\alpha}) \wedge \theta_{\alpha} \wedge \phi_{\alpha\beta} + \operatorname{Ad}(\phi_{\beta\alpha}) \cdot \tilde{D}(\theta_{\alpha}) - \phi_{\beta\alpha} \wedge \theta_{\alpha} \wedge \tilde{D}(\phi_{\alpha\beta}),$$
(10.4)

and also,

$$\theta_{\beta} \wedge \theta_{\beta} = \operatorname{Ad}(\phi_{\beta\alpha})(\theta_{\alpha} \wedge \theta_{\alpha}) + \phi_{\beta\alpha}\tilde{D}(\phi_{\alpha\beta}) \wedge \phi_{\beta\alpha}\tilde{D}(\phi_{\alpha\beta}) + \phi_{\beta\alpha}\tilde{D}(\phi_{\alpha\beta}) \wedge \operatorname{Ad}(\phi_{\beta\alpha}) \cdot \theta_{\alpha} + \operatorname{Ad}(\phi_{\beta\alpha}) \cdot \theta_{\alpha} \wedge \phi_{\beta\alpha}\tilde{D}(\phi_{\alpha\beta}).$$

Note that $\tilde{D}(\phi_{\beta\alpha})\phi_{\alpha\beta} = -\phi_{\beta\alpha}\tilde{D}(\phi_{\alpha\beta})$ since $\tilde{D}(\phi_{\beta\alpha}\phi_{\alpha\beta}) = 0$. Thus, we get

$$\theta_{\beta} \wedge \theta_{\beta} = \operatorname{Ad}(\phi_{\beta\alpha})(\theta_{\alpha} \wedge \theta_{\alpha}) - \tilde{D}(\phi_{\beta\alpha}) \wedge \tilde{D}(\phi_{\alpha\beta}) - \tilde{D}(\phi_{\beta\alpha}) \wedge \theta_{\alpha} \wedge \phi_{\alpha\beta} + \phi_{\beta\alpha} \wedge \theta_{\alpha} \wedge \tilde{D}(\phi_{\alpha\beta})$$
(10.5)

Hence, by combining (10.4) and (10.5) on $U_{\alpha\beta}$, we have

$$\begin{split} \phi_{\beta} \circ \Omega_{\nabla} \circ \phi_{\beta}^{-1} &= (\theta_{\beta} \wedge \theta_{\beta} + \tilde{D}(\theta_{\beta})) \\ &= \operatorname{Ad}(\phi_{\beta\alpha})(\theta_{\alpha} \wedge \theta_{\alpha} + \tilde{D}(\theta_{\alpha})) \\ &= \operatorname{Ad}(\phi_{\beta\alpha})(\phi_{\alpha} \circ \Omega_{\nabla} \circ \phi_{\alpha}^{-1}) \,. \end{split}$$

This implies that $\Omega \in \tilde{A}_E^2(M)$. Now, assume that E admits a hermitian structure such that ∇ is a generalized hermitian connection with respect to h. Without loss of generality, we can assume that $(E,h)|_{U_{\alpha}}$ is isomorphic to $U_{\alpha} \times \mathbb{C}^l$ with constant hermitian structure. Then we can easily see that, on $U_{\alpha}, \overline{\theta_{\alpha}}^t = -\theta_{\alpha}$ and so, by Example 10.9, $\overline{\Omega_{\nabla}}^t = -\Omega_{\nabla}$. Note that, using (10.3), we have, for any local $s_i \in \tilde{A}_E^{k_i}$ (i = 1, 2),

$$Dh(s_1, s_2) = h(\nabla s_1, s_2) + (-1)^{k_1} h(s_1, \nabla s_2).$$

This implies that for $s_i \in \tilde{A}_E^0$,

$$0 = \tilde{D}(\tilde{D}h(s_1, s_2)) = \tilde{D}(h(\nabla s_1, s_2) + h(s_1, \nabla s_2)) = h(\Omega_{\nabla} s_1, s_2) + h(s_1, \Omega_{\nabla} s_2).$$
(10.6)

If we further assume that ∇ is compatible with the GCS, we get,

$$\Omega_{\nabla} = \nabla^2 = (\nabla^{1,0})^2 + \nabla^{1,0} \circ \tilde{d}_L + \tilde{d}_L \circ \nabla^{1,0}.$$

Thus, $h(\Omega_{\nabla} s_1, s_2)$ and $h(s_1, \Omega_{\nabla} s_2)$ are of type (2, 0) + (1, 1) and (1, 1) + (0, 2), respectively. So, by (10.6), $(\nabla^{1,0})^2 = 0$. We have proved the following.

Proposition 10.10. Let E be an SGH vector bundle over M with a hermitian structure h. Let ∇ be a smooth generalized connection with curvature Ω_{∇} . Then

(1) If ∇ is a generalized hermitian connection with respect to h, Ω_{∇} satisfies

 $h(\Omega_{\nabla}s_1, s_2) + h(s_1, \Omega_{\nabla}s_2) = 0$ for any sections s_1, s_2 .

(2) If ∇ is compatible with the GCS, then Ω_{∇} has no (0,2)-part, that is,

$$\Omega_{\nabla} \in (\tilde{A}_E^{2,0} \oplus \tilde{A}_E^{1,1})(M) \,.$$

(3) If ∇ is a generalized Chern connection on (E,h), Ω_{∇} is of type (1,1), skewhermitian and real.

Recall the transversely holomorphic symplectic foliation \mathscr{S} of M and the corresponding leaf space M/\mathscr{S} . We have seen that a smooth generalized connection on an SGH vector bundle E over M with trivializations $\{U_{\alpha}, \phi_{\alpha}\}$ is equivalent to a family $\{\theta_{\alpha} \in \tilde{A}^{1}_{\operatorname{End}(E)|_{U_{\alpha}}}(U_{\alpha})\}$ satisfying (10.2). If each θ_{α} is constant along the leaves of \mathscr{S} , that is, if we replace \tilde{A}^{\bullet} by A^{\bullet} , we get the following notion.

Definition 10.11. Let E be an SGH vector bundle on M.

(1) A transverse generalized connection on E, is a \mathbb{C} -linear sheaf homomorphism

$$\nabla: A^0_E \longrightarrow A^1_E$$

which satisfies the Leibniz rule

$$\nabla(fs) = Df \otimes s + f\nabla(s)$$

for any local function $f \in F_M$ and any local section s of $F_M(E)$.

(2) A transverse generalized curvature is the curvature of a transverse generalized connection ∇ , denoted by Ω_{∇} .

Remark 10.12. A transverse generalized connection is also a smooth generalized connection in the sense that given a transverse generalized connection ∇ , we can consider a \mathbb{C} -linear sheaf homomorphism

$$\hat{\nabla}: \hat{A}^0_E = C^\infty_M \otimes_{F_M} A^0_E \longrightarrow \hat{A}^1_E = C^\infty_M \otimes_{F_M} A^1_E ,$$

defined by

$$\tilde{\nabla}(fs) = \tilde{D}f \otimes s + f\nabla s$$

for any local smooth function f and any local section $s \in A_E^0$. One can check that $\tilde{\nabla}$ is a smooth generalized connection.

Remark 10.13. A smooth generalized connection always exists. A transverse generalized connection exists locally. For it to exist globally we need a smooth partition of unity, which is constant along the leaves. If we assume M/\mathscr{S} is a smooth orbifold, such a partition of unity exists. Henceforth, in this section, we always assume that M/\mathscr{S} is a smooth orbifold.

We can replicate all the definitions and results for smooth generalized connections in this section, except those concerning hermitian structure, to transversely generalized connections by making the following substitutions.

	Replaced by
C_M^∞	F_M
Ã∙	A^{\bullet}
$\tilde{A}^{ullet,ullet}$	$A^{\bullet, \bullet}$
\tilde{D}	D
$ ilde{d_L}$	d_L

TABLE 1. Replacement table

For the results concerning the generalized hermitian connection, some extra care is needed. Consider the trivial SGH vector bundle $E = M \times \mathbb{C}^r$ with a hermitian structure h and let ∇ be a smooth generalized connection which satisfies (10.3). Any hermitian metric h given on E is given by a function, again denoted by h, on M that associates to any $x \in M$, a positive-definite hermitian matrix $h(x) = (h_{ij}(x))$. So we can think of h as a smooth global section of $E^* \otimes E^*$, that is,

$$h \in C^{\infty}_M(M, E^* \otimes E^*)$$
.

Now ∇ is of the form $\nabla = \tilde{D} + \theta$ for some $\theta = (\theta_{ij}) \in \tilde{A}^1_{\operatorname{End}(E)(M)}$. Let e_i be the constant *i*-th unit vector considered as a section of E. The assumption on ∇ will yield

$$\tilde{D}h(e_i, e_j) = h(\sum_k \theta_{ki} e_k, e_j) + h(e_i, \sum_l \theta_{lj} e_j)$$

or equivalently $\tilde{D}h = \theta^t \cdot h + h \cdot \overline{\theta}$. Furthermore, if we assume that ∇ is compatible with the GCS, then θ is of type (1,0). This implies

$$\tilde{d}_L h = h \cdot \overline{\theta}$$
$$\implies \theta = \overline{h}^{-1} \tilde{d}_L h$$

This shows that hermitian structure uniquely determines the smooth generalized connection. Thus, for a transverse generalized connection, we would like to have a hermitian metric which is constant along the leaves.

Definition 10.14. A hermitian metric h on an SGH vector bundle E is called a *trans*verse hermitian metric if $h \in F_M(M, E^* \otimes E^*)$, that is, h is constant along the leaves of \mathscr{S} .

Remark 10.15. Our assumption that M/\mathscr{S} is a smooth orbifold ensures that a transverse hermitian metric always exists.

With this notion of transverse hermitian metric and using the substitutions in Table 1, we can replicate all the relevant definitions and extend the results in Proposition 10.7 and Proposition 10.10 to the transverse generalized connections. In particular, we have the following.

Theorem 10.16. Let E be an SGH vector bundle over M such that M/S is a smooth orbifold. Let h be a transverse hermitian metic on E.

- (1) There exists a unique transverse generalized hermitian connection ∇ on E with respect to h which is also compatible with the GCS. This smooth generalized connection is called transverse generalized Chern connection.
- (2) The transverse generalized curvature of ∇ , Ω_{∇} is of type (1,1), skew-hermitian and real.
- (3) The space of transverse generalized connections on E, compatible with the GCS, forms an affine space over the \mathbb{C} -vector space $A^{1,0}_{\operatorname{End}(E)}(M)$.

10.1. Generalized Chern class for SGH vector bundles

Let $E \longrightarrow M$ be an SGH vector bundle over M of complex rank l. Then, following Subsection 9.1, consider the following characteristic polynomial

$$\det\left(I - t\frac{A}{2\pi i}\right) = \sum_{j=0}^{l} g_j(A) t^j,$$

where $g_j \in \mathbb{C}[M_l(\mathbb{C})]$ is the elementary symmetric polynomial of degree j and I is the identity matrix. Then, we can define an analogue of Chern classes similar to the classical case, as follows.

Definition 10.17. Let E be an SGH vector bundle over M. The *j*-th generalized Chern class of E, denoted by $\mathbf{g}c_j(E)$, is defined as the image of g_j under the generalized Chern-Weil homomorphism, that is,

$$\mathbf{g}c_j(E) := \Phi(g_j) \,,$$

where Φ as defined in (9.5).

Example 10.18. Let E be an SGH vector bundle over M where the leaf space M/\mathscr{S} admits an orbifold structure. Let ∇ be the transverse generalized Chern connection and Ω_{∇} be its curvature. Then $\mathbf{g}_{c_1}(E) = -\frac{1}{2\pi i}[\operatorname{Trace}(\Omega_{\nabla})].$

Remark 10.19. It is worth noting that if we substitute F_M with \mathcal{O}_M in Definition 10.11 and refer to Remark 3.12, we get a GH connection on an SGH vector bundle as defined by Lang et al [22, Definition 4.1]. In this framework, the subsequent result has been established concerning the existence of a GH connection on an SGH vector bundle.

Theorem 10.20. ([22, Section 4.1–4.2]) Let E be an SGH vector bundle over a regular GC manifold. Then, the following are equivalent

- (1) E admits a GH connection.
- (2) The short exact sequence, as defined in (6.2), splits.
- (3) b(E) = 0 where b(E) is the Atiyah class of the SGH vector bundle E as defined in Definition 6.1.

Theorem 10.21. Consider E as an SGH vector bundle over a regular GC manifold M. Let P denote the corresponding SGH principal bundle, as in (4.4). Then, E admits a GH connection if and only if P admits a GH connection.

Proof. Follows from Theorem 5.5, Theorem 6.4 and Theorem 10.20.

11. Generalized holomorphic Picard group

11.1. Generalized exponential short exact sequence

Let M be a smooth manifold. Let $C_M^{\infty,*}$ be the sheaf of smooth \mathbb{C}^* -valued functions on M, and let $\{\mathbb{Z}\}$ denote the locally constant sheaf over M whose stalk at each point is \mathbb{Z} . Consider the exponential map $\mathbb{C} \longrightarrow \mathbb{C}^*$ defined by $\exp(z) = e^{2\pi i z}$. Then for any open set $U \subseteq M$ and $f \in C_M^{\infty}(U)$, the map exp induces a map, again denoted by exp,

$$\exp: C_M^{\infty}(U) \longrightarrow C_M^{\infty,*}(U) \tag{11.1}$$

defined by $\exp(f)(x) = e^{2\pi i f(x)}$ for all $x \in U$. This induces a morphism of sheaves, again denoted by exp,

$$\exp: C_M^{\infty} \longrightarrow C_M^{\infty,*} \,. \tag{11.2}$$

Note that any $k \in \{\mathbb{Z}\}(U)$ is in the kernel of exp, that is, $\{\mathbb{Z}\}(U) \subseteq \ker(\exp)$ where exp is as in (11.1). To show the other side, consider $f = w + iv \in C^{\infty}_{M}(U)$ such that

$$\exp(w + iv) = 1$$

Here $v, w: U \longrightarrow \mathbb{R}$ are smooth maps. Then one observes that, for all $x \in U$,

$$e^{-2\pi v(x)}(\cos 2\pi w(x) + i\sin 2\pi w(x)) = 1,$$

$$\implies e^{-2\pi v(x)}(\cos 2\pi w(x)) = 1 \text{ and } e^{-2\pi v(x)}(\sin 2\pi w(x)) = 0;$$

$$\implies \cos 2\pi w(x) > 0 \text{ and } \sin 2\pi w(x) = 0 \text{ (as } e^{-2\pi v(x)} > 0).$$

Then there exists a smooth map $g: U \longrightarrow \mathbb{Z} \subset \mathbb{R}$ such that 2w(x) = g(x) for all $x \in U$. Thus w is a locally constant function. Now for any $x \in U$, g(x) is even. Thus, for all $x \in U$, $w(x) \in \mathbb{Z}$ and $\cos 2\pi w(x) = 1$. This implies $e^{-2\pi v(x)} = 1$ and so v(x) = 0. This shows that $f \in \{\mathbb{Z}\}(U)$, and hence

$$\ker(\exp) = \{\mathbb{Z}\}(U) \,.$$

Thus we get the following exact sequence of sheaves over M,

$$0 \longrightarrow \{\mathbb{Z}\} \longleftrightarrow C_M^{\infty} \xrightarrow{\exp} C_M^{\infty,*} \quad . \tag{11.3}$$

To show that exp is a surjective map of sheaves, it is enough to show that for any $x \in M$, the map $C_{M,x}^{\infty} \xrightarrow{\exp} C_{M,x}^{\infty,*}$ is onto. For that, it is enough to show that, for any simply connected open set $U \subset M$, the map exp, in (11.1), is onto.

Let $U \subset M$ be a simply connected open set and $g \in C_M^{\infty,*}(U)$. Note that the map $\mathbb{C} \xrightarrow{\exp} \mathbb{C}^*$ is a holomorphic covering map and \mathbb{C} is the universal cover. Since U is simply connected, there exists a unique smooth map $f \in C_M^{\infty}(U)$ such that the following diagram commutes

$$U \xrightarrow{f} \bigcup_{\substack{\exp \\ g}} \bigcup_{\substack{\exp \\ \mathbb{C}^*}}^{\mathbb{C}} \text{ that is, } g = \exp(f).$$

Thus the map in (11.2) is onto. This implies the following

Proposition 11.1. Let M be a smooth manifold. Then we have the following short exact sequence of sheaves

$$0 \longrightarrow \{\mathbb{Z}\} \longleftrightarrow C_M^{\infty} \xrightarrow{\exp} C_M^{\infty,*} \longrightarrow 0 \quad . \tag{11.4}$$

where C_M^{∞} , $C_M^{\infty,*}$ and $\{\mathbb{Z}\}$ are sheaves over M with their usual meanings.

Now, let M be a GC manifold and let \mathcal{O}_M^* be the sheaf of \mathbb{C}^* -valued GH functions over M. One can see that \mathcal{O}_M^* is a subsheaf of \mathcal{O}_M which is again subsheaf of C_M^{∞} . Note that, given any open set $U \subseteq M$ and any smooth map $f : U \longrightarrow \mathbb{C}$, we have $d(\exp(f)) = \exp(f) df$. This implies

$$d_L(\exp(f)) = \exp(f) d_L f$$

where d_L as in (8.1). By Corollary 8.4, we can see that

$$f \in \mathcal{O}_M(U)$$
 if and only if $\exp(f) \in \mathcal{O}_M^*(U)$.

This shows that we can restrict the short exact sequence in Proposition 11.1 to \mathcal{O}_M which gives us the following.

Theorem 11.2. Let M be GC manifold. Then we have the following short exact sequence of sheaves over M

$$0 \longrightarrow \{\mathbb{Z}\} \longleftrightarrow \mathcal{O}_M \xrightarrow{\exp} \mathcal{O}_M^* \longrightarrow 0 \quad . \tag{11.5}$$

11.2. GH Picard Group

Let E be an SGH line bundle over a GC manifold M with local trivializations $\{U_{\alpha}, \phi_{\alpha}\}$. The transition functions $\phi_{\alpha\beta}$, as defined in Theorem 3.2, are clearly non-vanishing GH functions by Lemma 3.11, that is, $\phi_{\alpha\beta} \in \mathcal{O}_M^*(U_{\alpha} \cap U_{\beta})$, and satisfy

$$\begin{aligned}
\phi_{\alpha\beta} \cdot \phi_{\beta\alpha} &= 1; \\
\phi_{\alpha\beta} \cdot \phi_{\beta\gamma} \cdot \phi_{\gamma\alpha} &= 1.
\end{aligned}$$
(11.6)

For any collection of nonzero GH functions $\{g_{\alpha} \in \mathcal{O}_{M}^{*}(U_{\alpha})\}\)$, we can define an alternative trivialization of E over $\{U_{\alpha}\}$ by

$$\phi_{\alpha}^{'} = g_{\alpha} \cdot \phi_{\alpha};$$

and the corresponding transition functions $\{\phi'_{\alpha\beta}\}$ will then be given by

$$\phi'_{\alpha\beta} = \frac{g_{\alpha}}{g_{\beta}} \cdot \phi_{\alpha\beta} \,. \tag{11.7}$$

One can see that any other trivialization of E over $\{U_{\alpha}\}$ can be obtained in this way.

On the other hand, given any collection of GH functions $\{\phi_{\alpha\beta} \in \mathcal{O}_M^*(U_\alpha \cap U_\beta)\}$, satisfying (11.6), we can construct an SGH line bundle E with transition functions $\{\phi_{\alpha\beta}\}$ by taking the union of $U_\alpha \times \mathbb{C}$ overall α and identifying $z \times \mathbb{C}$ in $U_\alpha \times \mathbb{C}$ and $U_\beta \times \mathbb{C}$ via multiplication by $\phi_{\alpha\beta}(z)$. Any two such collections of GH function $\{\phi_{\alpha\beta}, \phi'_{\alpha\beta} \in \mathcal{O}_M^*(U_\alpha \cap U_\beta)\}$, satisfying (11.6), define isomorphic SGH line bundles over $\{U_\alpha\}$ if and only if there exists a collection of nonzero GH functions $\{g_\alpha \in \mathcal{O}_M^*(U_\alpha)\}$, satisfying (11.7).

Note that the transition functions $\{\phi_{\alpha\beta} \in \mathcal{O}_M^*(U_\alpha \cap U_\beta)\}$ of E over $\{U_\alpha\}$ represents a Čech 1-cochain on M with coefficients in \mathcal{O}_M^* and the relations in (11.6) show that $\{\phi_{\alpha\beta}\}$ is indeed a Čech 1-cocycle. Moreover, by the last two paragraphs, we can see that

any two cocycles $\{\phi_{\alpha\beta}\}$ and $\{\phi'_{\alpha\beta}\}$ define isomorphic SGH line bundles if and only if $\{\phi_{\alpha\beta} \cdot (\phi'_{\alpha\beta})^{-1}\}$ is a Čech co-boundary. This implies that any SGH bundle isomorphism class of an SGH line bundle over M defines a unique element in $H^1(M, \mathcal{O}_M^*)$ and vice versa.

Consider the set \mathscr{E}_1 as defined in Proposition 4.5. We can give a group structure, denoted by τ , on \mathscr{E}_1 where multiplication is given by tensor product and inverses by dual bundles. Denote the group (\mathscr{E}_1, τ) by $\mathcal{G}\operatorname{Pic}(M)$, that is,

$$\mathcal{G}\operatorname{Pic}(M) := (\mathscr{E}_1, \tau). \tag{11.8}$$

By the last paragraph, we have proved the following.

Theorem 11.3. For any GC manifold M, $\mathcal{G}\operatorname{Pic}(M) \cong H^1(M, \mathcal{O}_M^*)$ as groups.

Definition 11.4. \mathcal{G} Pic(M) is called the *generalized holomorphic* (GH) Picard Group of M.

12. DUALITIES AND VANISHING THEOREMS FOR SGH VECTOR BUNDLES

In this section, we extend some classical results like Serre duality, Poincaré duality, Hodge decomposition and vanishing theorems to the cohomology theory of Section 8.1 following the approach of [2] and [18].

12.1. Generalized Serre duality and Hodge decomposition

Let M^{2n} be a compact regular GC manifold of type k. Then the leaf space M/\mathscr{S} , as defined in (7.2), is a compact space. Let us assume M/\mathscr{S} is a smooth orbifold. Then, by the integrability condition of the GCS, M/\mathscr{S} is a complex orbifold, and hence, orientable. Thus the cohomology $H^{2k}(M/\mathscr{S})$ is nontrivial. Therefore, there exists a (2n-2k)-form χ on M (see [2, Section 2.8]) which restricts to a volume form on each leaf such that for any $X_1, \ldots, X_{2n-2k} \in C^{\infty}_{\mathbb{R}}(T\mathscr{S})$ and $Y \in C^{\infty}_{\mathbb{R}}(TM)$,

$$d\chi(X_1, \dots, X_{2n-2k}, Y) = 0.$$
(12.1)

Fix a Riemannian metric on the leaf space. This induces a transverse Riemannian metric on M. We can complete the transverse metric by a Riemannian metric along the leaves to obtain a Riemannian metric on M for which the leaves are minimal. In fact, χ is associated to this metric.

Now, define a Hodge-star operator on A^{\bullet} ,

$$\star: A^{\bullet} \longrightarrow A^{2k-\bullet} \,, \tag{12.2}$$

as follows: Let U be an open set in M on which the GCS is equivalent to a product GCS (see Theorem 2.17). This implies that the symplectic foliation on U is trivial. Let e_1, \ldots, e_{2k} be transverse generalized 1-forms such that $\{e_1, \ldots, e_{2k}\}$ is an orthonormal frame of $A^1(U)$. Then, for any $r > 0, \star : A^r(U) \longrightarrow A^{2k-r}(U)$ is defined by,

$$\star(e_{i_1} \wedge e_{i_2} \wedge \dots \wedge e_{i_r}) = \operatorname{Sign}(i_1, \dots, i_r, j_1, \dots, j_{2k-r}) e_{j_1} \wedge e_{j_2} \wedge \dots \wedge e_{j_{2k-r}}$$
(12.3)

where $\{j_1, \ldots, j_{2k-r}\}$ is the increasing complementary sequence of $\{i_1, \ldots, i_r\}$ in the set $\{1, 2, \ldots, 2k\}$ and $\text{Sign}(i_1, \ldots, i_r, j_1, \ldots, j_{2k-r})$ denotes the sign of the permutation $\{i_1, \ldots, i_r, j_1, \ldots, j_{2k-r}\}$. A simple calculation will show that

$$\star \star = (-1)^{r(2k-r)} \,. \tag{12.4}$$

Define a hermitian product on $A^{r}(M)$, by

$$h(\alpha,\beta) := \int_{M} \alpha \wedge \overline{\star\beta} \wedge \chi \,. \tag{12.5}$$

Define another operator $D^*: A^r \longrightarrow A^{r-1}$ by

$$D^* := (-1)^{2k(r-1)-1} \star D \star .$$
(12.6)

For any $\alpha \in A^{r-1}(M)$ and $\beta \in A^r(M)$,

$$d(\alpha \wedge \star\beta \wedge \chi) = D\alpha \wedge \star\beta \wedge \chi - \alpha \wedge \star D^*\beta \wedge \chi + (-1)^{2k-1}\alpha \wedge \star\beta \wedge d\chi$$

Using (12.1) and integrating both sides, we get $h(D\alpha, \beta) = h(\alpha, D^*\beta)$. The operator D^* is called the formal adjoint of D.

Since M/\mathscr{S} is a complex orbifold, \mathscr{S} is hermitian as well. The operator \star induces a (vector space) isomorphism between $A^{p,q}(M)$ and $A^{k-q,k-p}(M)$, that is,

$$A^{p,q}(M) \cong A^{k-q, k-p}(M)$$
, (as \mathbb{C} -vector spaces),

where $A^{p,q}$ as defined in (8.5). Moreover, $D = d_L + d_{\overline{L}}$ on $A^{p,q}$ where $d_L, d_{\overline{L}}$ are defined as in (8.11). Then the operator D^* , restricted to $A^{p,q}$, decomposes into the sum of two operators

$$d_L^* := - \star \ d_{\overline{L}} \star;$$
$$d_{\overline{L}}^* := - \star \ d_L \star,$$

respectively of type (-1, 0) and (0, -1). One can see that d_L^* and $d_{\overline{L}}^*$ are the formal adjoints of $d_{\overline{L}}$ and d_L , respectively. Define the following operators

$$\Delta_D := D^* D + DD^*;$$

$$\Delta_{d_L} := d_{\overline{L}}^* d_L + d_L d_{\overline{L}}^*.$$
(12.7)

Note that, similar to the classical case, both Δ_D and Δ_{d_L} are self-adjoint.

For any $p, q, r \ge 0$, define

$$\mathcal{H}_D^r := \ker(\Delta_D) = \{ \alpha \in A^r(M) \mid D\alpha = D^*\alpha = 0 \};$$

$$\mathcal{H}_{d_{\overline{L}}}^{p,q} := \ker(\Delta_{d_{\overline{L}}}) = \{ \alpha \in A^{p,q}(M) \mid d_{\overline{L}}\alpha = d_L^*\alpha = 0 \};$$

$$\mathcal{H}_{d_L}^{p,q} := \ker(\Delta_{d_L}) = \{ \alpha \in A^{p,q}(M) \mid d_L\alpha = d_{\overline{L}}^*\alpha = 0 \}.$$
 (12.8)

Definition 12.1. A form $\alpha \in \mathcal{H}_D^r$ is called a transverse GH harmonic form of order r and if $\alpha \in \mathcal{H}_{d_r}^{p,q}$, it's called transverse GH form of type (p,q).

Theorem 12.2. Let M be a compact regular GC manifold of type k. Let \mathscr{S} be the induced transversely holomorphic foliation. Assume that M/\mathscr{S} is a smooth orbifold. Then we have the following.

- (1) \mathcal{H}_D^{\bullet} and $\mathcal{H}_{d_L}^{\bullet,\bullet}$ both are finite dimensional.
- (2) There are orthogonal decompositions

(a)
$$A^{\bullet}(M) = \mathcal{H}_D^{\bullet} \oplus \operatorname{img}(\Delta_D) = \mathcal{H}_D^{\bullet} \oplus \operatorname{img}(D) \oplus \operatorname{img}(D^*)$$
,

(b)
$$A^{\bullet,\bullet} = \mathcal{H}_{d_L}^{\bullet,\bullet} \oplus \operatorname{img}(\Delta_{d_L}) = \mathcal{H}_{d_L}^{\bullet,\bullet} \oplus \operatorname{img}(d_L) \oplus \operatorname{img}(d_{\overline{L}}^*).$$

Proof. Since M/\mathscr{S} is a compact complex orbifold, A^{\bullet} and $A^{\bullet,\bullet}$ both are hermitian vector bundles over M. Now, a simple local coordinate calculation shows that both Δ_D and Δ_{d_L} are strongly elliptic operators. This implies that the complexes $\{A^{\bullet}, D\}$ and $\{A^{\bullet,\bullet}, d_L\}$ both are transversely elliptic. Thus by [2, Theorem 2.7.3], we are done. \Box

Corollary 12.3. Let $H_D^{\bullet}(M)$ and $H_{d_L}^{\bullet,\bullet}(M)$ are defined as in (8.13), (8.14). Then $H_D^{\bullet}(M)$ and $H_{d_L}^{\bullet,\bullet}(M)$ are finite dimensional and isomorphic to \mathcal{H}_D^{\bullet} and $\mathcal{H}_{d_L}^{\bullet,\bullet}$, respectively.

Proof. Follows from Theorem 12.2.

The operator \star induces a \mathbb{C} -linear isomorphism

$$\star: \mathcal{H}_{d_L}^{\bullet,*}(M) \cong \mathcal{H}_{d_{\overline{L}}}^{k-*,k-\bullet}(M) \,.$$

On the other hand, consider the following hermitian map

$$\tilde{h}: A^{\bullet}(M) \times A^{2k-\bullet}(M) \longrightarrow \mathbb{C}$$

defined by $\tilde{h}(\alpha,\beta) = \int_M \alpha \wedge \beta \wedge \chi$. It induces a non-degenerate pairing

$$\Phi: H^{\bullet}_D(M) \times H^{2k-\bullet}_D(M) \longrightarrow \mathbb{C}.$$

Theorem 12.4. Let M be a compact regular GC manifold of type k. Let \mathscr{S} be the induced transversely holomorphic foliation. Assume that M/\mathscr{S} is a smooth orbifold. Then

(1) $H_D^{\bullet}(M)$ satisfies the genralized Poincaré duality, that is,

$$H_D^{\bullet}(M) \cong (H_D^{2k-\bullet}(M))^*$$

(2) $H_{d_L}^{\bullet,\bullet}(M)$ satisfies the generalized Serre duality, that is,

$$H_{d_L}^{\bullet,\bullet}(M) \cong (H_{d_L}^{k-\bullet,k-\bullet}(M))^* \,.$$

(3) Moreover, if S is also transversely Kählerian, we have a generalized Hodge decomposition,

$$H_D^{\bullet}(M) = \bigoplus_{p+q=\bullet} H_{d_L}^{p,q}(M) \,.$$

Proof. (1) and (2) follows from the preceding discussion.

(3) Since \mathscr{S} is transversely Kählerian, we can prove, analogous to the classical Kähler case, that $\Delta_D = 2\Delta_{d_L}$. Since $A^{\bullet}(M) = \bigoplus_{p+q=\bullet} A^{p,q}(M)$, every α is a transverse GH harmonic form of order \bullet if and only if its each component is a transverse GH harmonic form of type (p,q) where $p + q = \bullet$. Then using Theorem 12.2, we have the direct decomposition

$$H_D^{\bullet}(M) = \bigoplus_{p+q=\bullet} H_{d_L}^{p,q}(M) \,.$$

As the complex conjugation operator induces an isomorphism (of real vector spaces) $H_{d_L}^{\bullet,*}(M) \cong H_{d_L}^{*,\bullet}(M)$, the operator \star also induces a unitary isomorphism

$$\overline{\star}: H^{\bullet,*}_{d_L}(M) \longrightarrow H^{k-\bullet,\,k-*}_{d_L}(M)$$

defined by $\overline{\star}(\alpha) = \star(\overline{\alpha}) = \overline{\star(\alpha)}$.

Let E be an SGH vector bundle on M with a transverse hermitian structure H. Then H can be considered as a \mathbb{C} -antilinear isomorphism $H : E \cong E^*$. Consider the following operators

(1)

$$\overline{\star}_E : A_E^{\bullet, \bullet} \longrightarrow A_{E^*}^{\bullet, -\bullet} \tag{12.9}$$

defined by $\overline{\star}_E(\phi \otimes s) = \overline{\star}(\phi) \otimes H(s)$ for any local sections $\phi \in A^{\bullet,\bullet}$ and $s \in F_M(E)$ where $\overline{\star}(\phi) = \star(\overline{\phi})$.

(2)

$$d_{L,E}^*: A_E^{\bullet, \bullet} \longrightarrow A_E^{\bullet, \bullet-1} \tag{12.10}$$

defined by $d_{L,E}^* = -\overline{\star}_{E^*} \circ d_{L,E^*} \circ \overline{\star}_E$ where $d_{L,E^*} : A_{E^*}^{\bullet,\bullet} \longrightarrow A_{E^*}^{\bullet,\bullet+1}$ is the natural extension of d_L , as defined in (8.11).

(3)
$$\Delta_{d_{L,E}} := d_{L,E}^* d_{L,E} + d_{L,E} d_{L,E}^*$$

Let M be a compact GC manifold. Then, we can define a natural hermitian scalar product on $A_E^{\bullet,\bullet}(M)$, similarly as in (12.5),

$$h_E(\alpha,\beta) := \int_M \alpha \wedge \overline{\star}_E(\beta) \wedge \chi \,. \tag{12.11}$$

for any local section $\alpha, \beta \in A_E^{\bullet, \bullet}(M)$ where \wedge is the exterior product on $A^{\bullet, \bullet}$ and the evaluation map $E \otimes E^* \longrightarrow \mathbb{C}$ in bundle part. Then, similarly, we can prove that

Lemma 12.5. $d_{L,E}^*$ is the formal adjoint of $d_{L,E}$ and $\Delta_{d_{L,E}}$ is self-adjoint.

Set
$$\mathcal{H}_{d_{L,E}}^{\bullet,\bullet} := \ker(\Delta_{d_{L,E}}) = \{ \alpha \in A_E^{\bullet,\bullet}(M) \mid d_{L,E}\alpha = d_{L,E}^*\alpha = 0 \}.$$

Theorem 12.6. (Generalized Hodge decomposition for SGH vector bundle) Let (E, H) be an SGH vector bundle with a transverse hermitian structure H, over a compact GC manifold M. Assume M/S is a smooth orbifold. Then

(1) $\mathcal{H}_{d_{L_{E}}}^{\bullet,\bullet}$ is finite dimensional.

(2)
$$A_E^{\bullet,\bullet}(M) = \mathcal{H}_{d_{L,E}}^{\bullet,\bullet} \oplus \operatorname{img}(\Delta_{d_{L,E}}) = \mathcal{H}_{d_{L,E}}^{\bullet,\bullet} \oplus \operatorname{img}(d_{L,E}) \oplus \operatorname{img}(d_{L,E}^*)$$

Proof. Follows from Theorem 12.2 by replacing $\{A^{\bullet,\bullet}, d_L\}$ and Δ_{d_L} with $\{A_E^{\bullet,\bullet}, d_{L,E}\}$ and $\Delta_{d_{L,E}}$, respectively.

Consider the natural pairing

$$\tilde{h}_E: A_E^{\bullet, \bullet}(M) \times A_{E^*}^{k-\bullet, k-\bullet}(M) \longrightarrow \mathbb{C}$$

defined by $\tilde{h}_E(\alpha,\beta) = \int_M \alpha \wedge \beta \wedge \chi$ where \wedge is the exterior product on $A^{\bullet,\bullet}$ and the evaluation map $E \otimes E^* \longrightarrow \mathbb{C}$ in bundle part.

Theorem 12.7. (Generalized Serre duality for SGH vector bundle) Let E be an SGH vector bundle with the same assumption as in Theorem 12.6. Then there exists a natural \mathbb{C} -linear isomorphism between $H_{d_L}^{\bullet,\bullet}(M, E)$ and $(H_{d_L}^{k-\bullet,k-\bullet}(M, E^*))^*$, that is,

$$H^{\bullet,\bullet}_{d_L}(M,E) \cong (H^{k-\bullet,k-\bullet}_{d_L}(M,E^*))^* \quad (as \ \mathbb{C}\text{-vector spaces}),$$

where k = Type(M).

Proof. Consider the natural pairing h_E . It induces a pairing

$$\Phi_E: H^{\bullet,\bullet}_{d_L}(M,E) \times H^{k-\bullet,k-\bullet}_{d_L}(M,E^*) \longrightarrow \mathbb{C}.$$

defined as $\Phi_E([\alpha], [\beta]) = \tilde{h}_E(\alpha, \beta)$ where $[\alpha], [\beta]$ denote the classes of α, β , respectively. One can easily check that this is well-defined. To show that Φ_E is non-degenerate, by Theorem 12.6, it is enough to show that for any $0 \neq \alpha \in \mathcal{H}_{d_{L,E}}^{\bullet,\bullet}$, there exist a $\beta \in \mathcal{H}_{d_{L,E^*}}^{\bullet,\bullet}$ such that $\int_M \alpha \wedge \beta \wedge \chi \neq 0$. Note that, $\overline{\star}_E$ induces a \mathbb{C} -antilinear isomorphism $\overline{\star}_E : \mathcal{H}_{d_{L,E^*}}^{\bullet,\bullet} \longrightarrow \mathcal{H}_{d_{L,E^*}}^{k-\bullet,k-\bullet}$. This implies there exist β s.t $\overline{\star}_E(\alpha) = \beta$. Thus $\Phi_E([\alpha], [\beta]) =$ $h_E(\alpha, \alpha) \neq 0$ and this proves the theorem. \Box

12.2. Generalized Vanishing Theorems

Let g be a transversely hermitian metric and I be the transverse complex structure corresponding to the GCS on M where M and M/\mathscr{S} satisfy the same conditions as before with one exception, namely, M need not be compact. Define a transverse generalized form of type (1, 1) by

$$\omega := q(I(\cdot), \cdot) \in A^{1,1}(M).$$

This form is called the transverse generalized fundamental form. We define four operators, in particular, an analogue \mathcal{L} of the Lefschetz operator, and a corresponding dual Lefschetz operator Λ , as follows.

(1)
$$\mathcal{L} : A^{\bullet} \longrightarrow A^{\bullet+2}; \quad \alpha \mapsto \alpha \wedge \omega,$$

(2) $\Lambda := \star^{-1} \circ \mathcal{L} \circ \star : A^{\bullet} \longrightarrow A^{\bullet-2},$
(3) $d_L^* := -\star d_{\overline{L}} \star,$
(4) $d_{\overline{L}}^* := -\star d_L \star,$

where \star is defined in (12.2). Note that d_L^* and d_L^* are well defined even if M is not compact. But if M is compact, they are formal adjoints with respect to the hermitian inner product h (see (12.5)).

Now, assume $D\omega = 0$. This implies that \mathscr{S} is transversely Kählerian with transversely Kähler metric g. Thus, M/\mathscr{S} is a Kähler orbifold. Trivial modification of the proofs of [18, Proposition 1.2.26, Proposition 3.1.12] yields the following identities analogous to the Kähler identities in the classical case.

Proposition 12.8. Let M be a regular GCS such that the leaf space M/\mathscr{S} is a Kähler orbifold. Then

(1)
$$[\Lambda, \mathcal{L}] = (k - (p+q)) \operatorname{Id}_{A^{p,q}}$$

(2)
$$[d_L, \mathcal{L}] = [d_{\overline{L}}, \mathcal{L}] = 0$$
 and $[d_L^*, \Lambda] = [d_{\overline{L}}^*, \Lambda] = 0$.

(3)
$$[d_L^*, \mathcal{L}] = id_{\overline{L}}, \ [d_{\overline{L}}, \mathcal{L}] = -id_L \ and \ [\Lambda, d_L] = -id_{\overline{L}}^*, \ and \ [\Lambda, d_{\overline{L}}] = id_L^*.$$

For the rest of this section, assume that M is compact and M/\mathscr{S} is a Kähler orbifold. Let E be an SGH vector bundle over M. Consider the natural extension of \mathcal{L} , Λ on $A_E^{\bullet,\bullet}$, which will be again denoted by \mathcal{L} , Λ , respectively. Fix a transverse hermitian structure on E (see Definition 10.14). Let ∇_E be the transverse generalized Chern connection and Ω_{∇} be its curvature. Let $\{U_{\alpha}, \phi_{\alpha}\}$ be an orthonormal trivialization of E. Then, on $U_{\alpha} \times \mathbb{C}^r$, with respect to such trivialization,

(1) $\overline{\star}_E$ can be identified with the complex conjugate $\overline{\star}$ of the operator \star defined in (12.3).

(2)
$$\nabla_E = D + \theta_{\alpha}$$
, $\nabla_E^{1,0} = d_{\overline{L}} + \theta_{\alpha}^{1,0}$ and $\theta_{\alpha}^* = -\theta_{\alpha}$.

(3)

$$(\nabla_E^{1,0})^* = -\overline{\star} \circ \nabla_{E^*}^{1,0} \circ \overline{\star} \quad (by \ (12.10))$$
$$= -\overline{\star} \circ (d_{\overline{L}} - \theta_{\alpha}^{1,0}) \circ \overline{\star} \quad (by \ (12.10))$$
$$= d_{\overline{L}}^* - (\theta_{\alpha}^{1,0})^* .$$
$$[\Lambda, \nabla_E^{0,1}] + i(\nabla_E^{1,0})^* = [\Lambda, d_L] + [\Lambda, \theta_{\alpha}^{0,1}] + id_{\overline{L}}^* - i(\theta_{\alpha}^{1,0})^*$$
$$= [\Lambda, \theta_{\alpha}^{0,1}] - i(\theta_{\alpha}^{1,0})^* \quad (by \ (3) \text{ Proposition } 12.8)$$

So, the global operator $[\Lambda, \nabla_E^{0,1}] + i(\nabla_E^{1,0})^*$ is linear. For any point $x \in M$, we can always choose an orthonormal trivialization $\{U_\alpha, \phi_\alpha\}$ such that $x \in U_\alpha$ and $\theta_\alpha(x) = 0$. Since M is compact, $(\nabla_E^{1,0})^* = -\overline{\star}_{E^*} \circ \nabla_{E^*}^{1,0} \circ \overline{\star}_E$ is the formal adjoint of $\nabla_E^{1,0}$.

Lemma 12.9. Let ∇_E be the transverse generalized Chern connection on E and Ω_{∇} be its curvature. Then, we have

- (1) $[\Lambda, \nabla_E^{0,1}] = -i((\nabla_E^{1,0})^*) = i(\overline{\star}_{E^*} \circ \nabla_{E^*}^{1,0} \circ \overline{\star}_E).$
- (2) For an arbitrary $\alpha \in \mathcal{H}_{d_{L,E}}^{\bullet,\bullet}$,

$$\frac{i}{2\pi}h_E(\Omega_{\nabla}\Lambda\alpha,\alpha) \le 0; \quad and \quad \frac{i}{2\pi}h_E(\Lambda\Omega_{\nabla}\alpha,\alpha) \ge 0,$$

where h_E is the natural hermitian product, defined in (12.11).

Proof. (1) follows from the preceding discussion.

(2) By Proposition 10.2, $\Omega_{\nabla} = \nabla_E^{1,0} \circ d_{L,E} + d_{L,E} \circ \nabla_E^{1,0}$. Let α be an element in $\mathcal{H}_{d_{L,E}}^{p,q}$. Since $\Lambda \alpha \in A_E^{p-1,q-1}(M)$, $\Omega_{\nabla} \Lambda \alpha \in A_E^{p,q}(M)$. So, we can compute

$$h_{E}(i\Omega_{\nabla}\Lambda\alpha,\alpha) = ih_{E}(\nabla_{E}^{1,0}d_{L,E}\Lambda\alpha,\alpha) + ih_{E}(d_{L,E}\nabla_{E}^{1,0}\Lambda\alpha,\alpha)$$

$$= ih_{E}(d_{L,E}\Lambda\alpha,(\nabla_{E}^{1,0})^{*}\alpha) + ih_{E}(\nabla_{E}^{1,0}\Lambda\alpha,d_{L,E}^{*}\alpha)$$

$$= h_{E}(d_{L,E}\Lambda\alpha,-i(\nabla_{E}^{1,0})^{*}\alpha) + 0 \quad (\text{as } \alpha \in \mathcal{H}_{d_{L,E}}^{p,q})$$

$$= h_{E}(d_{L,E}\Lambda\alpha,[\Lambda,\nabla_{E}^{0,1}]\alpha) \quad (\text{by }(1))$$

$$= h_{E}(d_{L,E}\Lambda\alpha,\Lambda\nabla_{E}^{0,1}\alpha) - h_{E}(d_{L,E}\Lambda\alpha,\nabla_{E}^{0,1}\Lambda\alpha)$$

$$= -h_{E}(d_{L,E}\Lambda\alpha,d_{L,E}\Lambda\alpha) \quad (\text{as } \nabla_{E}^{0,1} = d_{L,E})$$

$$\leq 0.$$

Similarly, we can show $h_E(i\Lambda\Omega_{\nabla}\alpha,\alpha)\geq 0$.

Definition 12.10.

(1) A real (1, 1)-transverse generalized form α (that is, $\alpha = \overline{\alpha}$) is called *(semi-)* positive if for all GH tangent vectors $0 \neq v \in \mathcal{G}M$, one has

$$-i\alpha(v,\overline{v}) > 0 \ (\geq 0)$$
.

(2) Let ∇ be a transverse generalized hermitian connection with respect to a transverse hermitian structure H on E such that $\Omega_{\nabla} \in A^{1,1}_{\operatorname{End}(E)}(M)$. The transverse generalized curvature Ω_{∇} is (Griffiths-) positive if, for any local section $0 \neq s \in F_M(E)$, one has

$$H(\Omega_{\nabla}(s), s)(v, \overline{v}) > 0$$

for all $0 \neq v \in \mathcal{G}M$.

Definition 12.11. An SGH line bundle E over M is positive if its first generalized Chern class $\mathbf{g}_{c_1}(E) \in H^2_D(M)$ can be represented by a closed positive (1, 1)-transverse generalized form where $\mathbf{g}_{c_1}(E)$ is defined in Example 10.18.

Theorem 12.12. Let M be a compact regular GC manifold of type k. Let the leaf space M/\mathscr{S} of the induced foliation be a Kähler orbifold. Let E be a positive SGH line bundle on M. Then, we have the following

(1) (Generalized Kodaira vanishing theorem)

$$H^q(M, (\mathcal{G}^*\mathbf{M})^p \otimes_{\mathcal{O}_M} \mathbf{E}) = 0 \quad for \ p+q > k.$$

(2) (Generalized Serre's theorem) For any SGH vector bundle E' on M, there exists a constant m_0 such that

$$H^q(M, \mathbf{E}' \otimes_{\mathcal{O}_M} \mathbf{E}^m) = 0 \quad for \ m \ge m_0 \ and \ q > 0.$$

Proof. Choose a transverse hermitian structure on E such that the curvature of the transverse generalized Chern connection ∇_E is positive, that is, $\frac{i}{2\pi}\Omega_{\nabla_E}$ is a transverse Kähler form (that is, D-closed transverse generalized fundamental form) on M. We endow M with this corresponding transverse Kähler structure.

(1) With respect to this transverse Kähler structure, the operator \mathcal{L} is nothing but the curvature operator $\frac{i}{2\pi}\Omega_{\nabla_E}$. Then, for $\alpha \in \mathcal{H}^{p,q}_{d_{L,E}}$,

$$0 \leq h_E(\frac{i}{2\pi}[\Lambda, \Omega_{\nabla_E}]\alpha, \alpha) \quad \text{(by (2) Lemma 12.9)}$$
$$= h_E([\Lambda, \mathcal{L}]\alpha, \alpha)$$
$$= (k - (p+q))h_E(\alpha, \alpha) \quad \text{(by (1) Proposition 12.8)}$$

By Corollary 8.10 and Theorem 12.6, we get

$$\mathcal{H}^{p,q}_{d_{L,E}} \cong H^{p,q}_{d_{L}}(M,E) \cong H^{q}(M,(\mathcal{G}^{*}\mathbf{M})^{p} \otimes_{\mathcal{O}_{M}} \mathbf{E}).$$

Hence $H^q(M, (\mathcal{G}^*\mathbf{M})^p \otimes_{\mathcal{O}_M} \mathbf{E}) = 0$ for p + q > k.

(2) Let $m \neq 0$. Choose a transverse hermitian structure on E' and denote its associated transverse generalized Chern connection by $\nabla_{E'}$. Then we have an induced

transverse Chern connection on $E'' := E' \otimes E^m$, denoted by ∇ , corresponding to the induced transverse hermitian structure,

$$\nabla = \nabla_{E'} \otimes 1 + 1 \otimes \nabla_{E^m} \,,$$

where ∇_{E^m} is induced by ∇_E . Its curvature is of the form

$$\frac{i}{2\pi}\Omega_{\nabla} = \frac{i}{2\pi}\Omega_{\nabla_{E'}} \otimes 1 + \frac{i}{2\pi}(1\otimes\Omega_{\nabla_{E^m}})$$
$$= \frac{i}{2\pi}\Omega_{\nabla_{E'}} \otimes 1 + m(1\otimes\frac{i}{2\pi}\Omega_{\nabla_E}) \quad (\text{as } \Omega_{\nabla_{E^m}} = m\Omega_{\nabla_E})$$

By (2) in Lemma 12.9, for $\alpha \in \mathcal{H}^{p,q}_{d_{L,E''}}$, we have

$$\begin{split} 0 &\leq \frac{i}{2\pi} h_{E''}([\Lambda, \Omega_{\nabla}]\alpha, \alpha) \\ &= \frac{i}{2\pi} h_{E''}([\Lambda, \Omega_{E'}\alpha, \alpha]) + m h_{E''}([\Lambda, \mathcal{L}]\alpha, \alpha) \\ &= \frac{i}{2\pi} h_{E''}([\Lambda, \Omega_{E'}]\alpha, \alpha) + m(k - (p+q))h_{E''}(\alpha, \alpha) \quad (by \ (1) \ \text{Proposition} \ 12.8) \,. \end{split}$$

Since $h_{E''}$ is a positive-definite hermitian matrix on each fiber of E'', we can consider the fiber wise Cauchy-Schwarz inequality

$$|h_{E''}([\Lambda, \Omega_{E'}]\alpha, \alpha)| \le ||[\Lambda, \Omega_{E'}]|| \cdot h_{E''}(\alpha, \alpha) \,.$$

By compactness of M, we have a global upper bound C for the operator norm $||[\Lambda, \Omega_{E'}]||$, independent of m, and a corresponding global inequality. Thus, we get,

$$0 \le \left| \frac{i}{2\pi} h_{E''}([\Lambda, \Omega_{E'}]\alpha, \alpha) \right| + (m(k - (p + q))) h_{E''}(\alpha, \alpha)$$
$$= \left(\frac{C}{2\pi} + (m(k - (p + q))) \right) h_{E''}(\alpha, \alpha) .$$

Hence, if $C + 2\pi m(k - (p+q)) < 0$, then $\alpha = 0$. When p = k and q > 0, $m > \frac{C}{2\pi} \ge \frac{C}{2\pi q}$ ensures $\alpha = 0$. So, if we take $m_0 > \frac{C}{2\pi}$, by Corollary 8.10 and Theorem 12.6, we get

$$\mathcal{H}^{k,q}_{d_{L,E''}} \cong H^q(M, (\mathcal{G}^*\mathbf{M})^k \otimes_{\mathcal{O}_M} (\mathbf{E}' \otimes_{\mathcal{O}_M} \mathbf{E}^{\mathbf{m}})) = 0 \quad \text{for } m \ge m_0 \text{ and } q > 0.$$

Now, we apply these arguments to the SGH bundle $(\mathcal{G}M)^k \otimes E'$ instead of E'. The constant m_0 might change in the process but this will prove the assertion.

13. Strong generalized Calabi-Yau manifold and its leaf space

In this section, we give some criteria on the GCS so that the leaf space of the associated symplectic foliation is a smooth torus, and therefore, satisfies the hypothesis that the leaf space be an orbifold, used in most of our results in this manuscript. This is a generalization of a result of Bailey et al. [4, Theorem1.9].

Let M^{2n} be a GC manifold with +i-eigenbundle L of $(TM \oplus T^*M) \otimes \mathbb{C}$. Consider the bundle $\bigwedge^{\bullet} T^*M \otimes \mathbb{C}$ as a spinor bundle for $(TM \oplus T^*M) \otimes \mathbb{C}$ with the following Clifford action

$$(X + \eta) \cdot \rho = i_X(\rho) + \eta \wedge \rho \quad \text{for } X + \eta \in (TM \oplus T^*M) \otimes \mathbb{C}$$

Then, there exits a unique line subbundle U_M of $\bigwedge^{\bullet} T^*M \otimes \mathbb{C}$, called the *canonical* line bundle associated to the GCS, which is annihilated by L under the above Clifford action.

At each point of M, U_M is generated by a

$$\rho = e^{B+i\omega}\Omega\,,$$

where B, ω are real 2-forms and $\Omega = \theta_1 \wedge \cdots \wedge \theta_k$ is a complex decomposable k-form where k is the type of the GCS at that point. By [14, 15], the condition $L \cap \overline{L} = \{0\}$ is equivalent to the non-degeneracy condition

$$\omega^{n-k} \wedge \Omega \wedge \overline{\Omega} \neq 0. \tag{13.1}$$

The involutivity of L, with respect to the Courant bracket, is equivalent to the following condition on any local trivialization ρ of U_M ,

$$d\rho = (X + \eta) \cdot \rho \,,$$

for some $X + \eta \in C^{\infty}(TM \oplus T^*M) \otimes \mathbb{C}$.

Definition 13.1. A GC manifold M of type k is said to be a generalized Calabi-Yau manifold if its canonical bundle U_M is a trivial bundle admitting a nowhere-vanishing global section ρ such that $d\rho = 0$ (cf. [14, 15]). M is called a strong generalized Calabi-Yau manifold if, in addition, ρ is such that $\Omega = \theta_1 \wedge \cdots \wedge \theta_k$ is globally decomposable and $d\theta_j = 0$ for $1 \leq j \leq k$.

Remark 13.2. Note that any generalized Calabi-Yau manifold is orientable because we get a global nowhere-vanishing volume form $\omega^{n-k} \wedge \Omega \wedge \overline{\Omega}$.

Example 13.3.

- (1) Any type 1 generalized Calabi-Yau manifold is a strong generalized Calabi-Yau manifold.
- (2) Any 6-dimensional nilmanifold with $(b_1, b_2) \in \{(4, 6), (4, 8), (5, 9), (5, 11), (6, 15)\}$ admits a type 2 strong generalized Calabi-Yau structure (cf. [10, Table 1]) where b_1 and b_2 are the first and second betti numbers, respectively.

Let M^{2n} be a compact connected strong generalized Calabi-Yau manifold of type k. Under some assumptions on the leaves of the induced foliation, we show that the foliation is simple. To show this, we need to use an extended version of the techniques used in [4, Section 1.2].

Let ρ be a nowhere-vanishing closed section of the corresponding canonical line bundle U_M . We can express ρ in the following form

$$\rho = e^{B + i\omega} \wedge \Omega$$

where B, ω are real 2-forms and $\Omega = \theta_1 \wedge \cdots \wedge \theta_k$ is a complex decomposable k-form with $d\theta_j = 0$ for $1 \leq j \leq k$. Fix $p \in \{1, \ldots, k\}$. Let $\theta_p = \operatorname{Re}(\theta_p) + i \operatorname{Im}(\theta_p)$ where $\operatorname{Re}(\theta_p)$ and $\operatorname{Im}(\theta_p)$ denote the real and imaginary parts of θ_p , respectively. First, we show that $[\operatorname{Re}(\theta_p)]$ and $[\operatorname{Im}(\theta_p)]$ are linearly independent in $H^1_{dR}(M, \mathbb{R})$.

If possible, let there exist a nontrivial linear combination, say

$$\lambda_R[\operatorname{Re}(\theta_p)] + \lambda_I[\operatorname{Im}(\theta_p)] = 0.$$

Fix $m_0 \in M$ and define the map $f: M \longrightarrow \mathbb{R}$ as

$$f(m) = \int_{[m_0,m]} (\lambda_R \operatorname{Re}(\theta_p) + \lambda_I \operatorname{Im}(\theta_p)),$$

where integral is taken over any path connecting m_0 to $m \in M$. The function f is well-defined as $\lambda_R \operatorname{Re}(\theta_p) + \lambda_I \operatorname{Im}(\theta_p)$ is exact. Without loss of generality, let $\lambda_R \neq 0$. Note that $\theta_p \wedge \overline{\theta_p} = -2i \operatorname{Re}(\theta_p) \wedge \operatorname{Im}(\theta_p)$. Then the non-degeneracy condition

$$\omega^{n-k} \wedge \left(\bigwedge_{j=1}^k \theta_j \wedge \overline{\theta_j}\right) \neq 0$$

implies that

$$\omega^{n-k} \wedge \left(\bigwedge_{\substack{j=1\\j\neq p}}^k \theta_j \wedge \overline{\theta_j} \right) \wedge df \neq 0 \,.$$

This shows that df is nowhere vanishing and so, f is a submersion. Therefore, f(M) is open. However, f(M) is also closed since M is compact. Thus $f(M) = \mathbb{R}$ which is a contradiction. Hence $[\operatorname{Re}(\theta_p)]$ and $[\operatorname{Im}(\theta_p)]$ are linearly independent.

Now, the non-degeneracy condition (13.1) is an open condition that gives us the freedom to choose $\theta_j \in \Omega^1(M, \mathbb{C})$ $(1 \leq j \leq k)$ such that $[\operatorname{Re}(\theta_j)]$ and $[\operatorname{Im}(\theta_j)]$ are still linearly independent in $H^1(M, \mathbb{Q})$. Then, we can consider the map

$$\tilde{f}: M \longrightarrow \mathbb{C}^k / \Gamma \cong \prod_j \mathbb{T}^2$$
 defined as $\tilde{f}(m) = \bigoplus_j \int_{[m_0,m]} \theta_j$,

where the integral is taken over any path connecting m_0 to m and

$$\Gamma = \oplus_j [\theta_j](H_1(M,\mathbb{Z}))$$

is a co-compact lattice in \mathbb{C}^k . As before, using the non-degeneracy condition, one can show that \tilde{f} is a surjective submersion.

Suppose S is a leaf of the induced foliation \mathscr{S} which is closed. Then S is a compact embedded submanifold in M. Let X_i be a complex vector field on M such that

$$\theta_l(X_j) = \delta_{lj} \quad \text{and} \quad \overline{\theta_l}(X_j) = 0,$$

where δ_{lj} is Kronecker delta and $l, j \in \{1, \ldots, k\}$. This is possible since the normal bundle \mathcal{N} of the foliation is trivial and the transverse holomorphic structure induces an integrable complex structure on \mathcal{N} so that $C^{\infty}(\mathcal{N}^{1,0*}) = \langle \theta_j | j = 1, \ldots, k \rangle$ and $C^{\infty}(\mathcal{N}^{0,1*}) = \langle \overline{\theta_j} | j = 1, \ldots, k \rangle$ where $\mathcal{N} \otimes \mathbb{C} = \mathcal{N}^{1,0} \oplus \mathcal{N}^{0,1}$ as defined in (7.1). Let $\operatorname{Re}(X_j)$ and $\operatorname{Im}(X_j)$ be the real and imaginary parts of X_j , respectively. Note that $\operatorname{Re}(X_j)$ and $\operatorname{Im}(X_j)$ are pointwise linearly independent and $\mathcal{L}_Y \Omega = \mathcal{L}_Y \overline{\Omega} = 0$ where $Y \in \{\operatorname{Re}(X_j), \operatorname{Im}(X_j) : 1 \leq j \leq k\}$. Therefore, these vector fields preserve the foliation \mathscr{S} which is determined by $\operatorname{ker}(\Omega \wedge \overline{\Omega})$.

Consider the map

$$\psi_S: S \times \mathbb{R}^{2k} \longrightarrow M$$
,

defined by

$$\psi_S(s,\lambda_1,\ldots,\lambda_{2k}) = \exp\left(\sum_{j=1}^k \left(\lambda_{2j-1}\operatorname{Re}(X_j) + \lambda_{2j}\operatorname{Im}(X_j)\right)\right)(s)$$

 ψ_S is a local diffeomorphism as $(\psi_S)_*(TS \oplus \mathbb{R}^{2k}) = TM$. Since $\operatorname{Re}(X_j)$ and $\operatorname{Im}(X_j)$ preserve the foliation \mathscr{S} , $\sum_{j=1}^k \left(\lambda_{2j-1}\operatorname{Re}(X_j) + \lambda_{2j}\operatorname{Im}(X_j)\right)$ also preserves \mathscr{S} . We conclude that all leaves in a neighborhood of S are diffeomorphic to S. More precisely, since S is compact, ψ_S provides a leaf preserving local diffeomorphism between a tubular neighborhood of S in M and $S \times \prod_j \mathbb{D}^2$. Here $\mathbb{D}^2 \subset \mathbb{R}^2$ is an open disk.

Let V be the set of points in M that lie in leaves that are diffeomorphic to S. Then V is an open subset of M. Let $q \in \overline{V}$. Let $\alpha : \mathbb{D}^{2n-2k} \longrightarrow M$ be a local parametrization of the leaf through q such that $\alpha(0) = q$. Then, the map $\psi : \mathbb{D}^{2n-2k} \times \prod_j \mathbb{D}^2 \longrightarrow M$ defined by

$$\psi(s,\lambda_1,\ldots,\lambda_{2k}) = \exp\left(\sum_{j=1}^k \left(\lambda_{2j-1}\operatorname{Re}(X_j) + \lambda_{2j}\operatorname{Im}(X_j)\right)\right) (\alpha(s))$$

is a again a leaf preserving local diffeomorphism. Here, $\mathbb{D}^{2n-2k} \times \prod_j \mathbb{D}^2$ is considering with the product GCS. So, $\operatorname{img}(\psi) \cap V \neq \emptyset$. Let $q' \in \operatorname{img}(\psi) \cap V$ and S' be the compact leaf through it. For some $(s, \lambda_1, \ldots, \lambda_{2k}) \in \mathbb{D}^{2n-2k} \times \prod_j \mathbb{D}^2$, we have

$$q' = \psi(s, \lambda_1, \dots, \lambda_{2k}).$$

By taking the inverse of exp, we can shows that $\psi_{S'}(q', -\lambda_1, \ldots, -\lambda_{2k}) \in \operatorname{img}(\alpha)$. Therefore, $\operatorname{img}(\alpha) \cap \operatorname{img}(\psi_{S'}) \neq \emptyset$. So, S' is diffeomorphic to the leaf through q via $\psi_{S'}$, which shows that $q \in V$. Since V is both open and closed and M is connected,

we have V = M. This conclude that M is a fibration (fibre bundle) $M \longrightarrow B$ over a compact connected 2k-dimensional smooth manifold. Now, θ_j $(1 \le j \le k)$ vanishes when restricted to a leaf by [15, Corollary 2.8]. Since θ_j is also closed, it is basic for this fibration, that is, B has 2k-number of linearly independent nowhere-vanishing closed real 1-forms.

Proposition 13.4. Let B be any smooth compact connected 2k-dimensional manifold. Suppose B has 2k linearly independent nowhere-vanishing closed real 1-forms. Then B is diffeomorphic to a product of 2-dimensional tori $\prod_{i=1}^{k} \mathbb{T}^{2}$.

Proof. Let $\{\theta_1, \ldots, \theta_{2k}\}$ be linearly independent nowhere-vanishing closed 1-forms on B. Note that $\wedge_j \theta_j$ is a volume form for B, which is an open condition. So, we can choose θ_j 's such that θ_j 's are linearly independent in $H^1(M, \mathbb{Q})$. Fix $m_0 \in B$ and consider the following map

$$\phi: B \longrightarrow \mathbb{R}^{2k} / \Gamma \cong \prod_{j=1}^{k} \mathbb{T}^2$$
 defined as $\phi(m) = \bigoplus_{j=1}^{2k} \int_{[m_0,m]} \theta_j$,

where integral is taken over any path connecting m_0 to m. Let $\Gamma = \bigoplus_{j=1}^{2k} [\theta_j](H_1(B,\mathbb{Z}))$. Then Γ is a co-compact lattice in \mathbb{R}^{2k} . One can easily see that

$$\left(\bigwedge_{\substack{j=1\\j\neq p}}^{2k}\theta_j\right)\wedge d\phi_p\neq 0\,,$$

where $\phi_p : B \longrightarrow \mathbb{R}/[\theta_p](H_1(B,\mathbb{Z})) \cong S^1$ is the natural projection of ϕ onto the *p*-th component. This implies that ϕ_j $(1 \leq j \leq 2k)$ is a submersion. Hence, ϕ is a submersion. It follows that ϕ is a local diffeomorphism. Since *B* is compact, ϕ is a proper map. Therefore, $\phi : B \longrightarrow \prod_{j=1}^k \mathbb{T}^2$ is a covering map and it induces an injective map

$$\pi_1(\phi): \pi_1(B) \longrightarrow \pi_1(\prod_{j=1}^k \mathbb{T}^2) \cong \bigoplus_{2k} \mathbb{Z}.$$

Then $\pi_1(B) \cong \bigoplus_l \mathbb{Z}$ for some $l \leq 2k$. Using the de Rham isomorphism and the universal coefficient theorem, we have $H^1_{dR}(B,\mathbb{R}) \cong \operatorname{Hom}(H_1(B,\mathbb{R}),\mathbb{R})$ and $H_1(B,\mathbb{R}) \cong H_1(B,\mathbb{Z}) \otimes_{\mathbb{Z}} \mathbb{R}$, respectively. Since the rank of $H^1_{dR}(B,\mathbb{R})$ is 2k, $\operatorname{Rank}(H_1(B,\mathbb{Z})) = 2k$. As $\pi_1(B) \cong H_1(B,\mathbb{Z})$ (since $\pi_1(B)$ is abelian), $\pi_1(B) \cong \bigoplus_{2k} \mathbb{Z}$. So, there exists a smooth covering map $\tilde{\phi} : \mathbb{R}^{2k} \longrightarrow B$, such that B is diffeomorphic to $\mathbb{R}^{2k}/\pi_1(B) \cong \prod_{j=1}^k \mathbb{T}^2$. \Box

We have proved the following result.

Theorem 13.5. Let M be a compact connected strong generalized Calabi-Yau manifold of type k. Let \mathscr{S} be the induced foliation. Then, the following statements hold.

(1) There exists a smooth surjective submersion $\tilde{f}: M \longrightarrow \prod_{i=1}^k \mathbb{T}^2$.

- (2) Suppose \mathcal{S} has a compact leaf. Then, we have:
 - (a) All leaves are diffeomorphic and compact. Their holonomy group is trivial.
 - (b) The leaf space M/S is a smooth manifold.
 - (c) The submersion \tilde{f} can be chosen so that the components of the fibers of \tilde{f} are the symplectic leaves of \mathscr{S} .

14. NILPOTENT LIE GROUPS, NILMANIFOLDS, AND SGH BUNDLES

In this section, we give a complete characterization of the leaf space of a left invariant GCS on a simply connected nilpotent Lie group and its associated nilmanifolds. Finally, we construct some examples of nontrivial SGH bundles on the Iwasawa manifolds which show that the category of SGH bundles is in general different from the category of holomorphic bundles on the leaf space.

Let G^{2n} be a simply connected nilpotent Lie group and \mathfrak{g} be its real lie algebra. Suppose G has a left-invariant GCS. Since G is diffeomorphic to \mathfrak{g} via the exponential map, any left-invariant GCS is regular of constant type, say k. The canonical line bundle, corresponding to a left-invariant GCS, is trivial as G is contractible. So, we can choose a global trivialization of the form

$$\rho = e^{B+i\omega} \wedge \Omega \,, \tag{14.1}$$

where B, ω are real left invariant 2-forms and $\Omega = \theta_1 \wedge \cdots \wedge \theta_k$ is a complex decomposable k-form with left invariant complex 1-forms θ_j $(1 \le j \le k)$.

Let \mathscr{S} be the induced foliation and \mathcal{N} be its normal bundle. Then we know that $T\mathscr{S} = \ker(\Omega \wedge \overline{\Omega})$. Using [1, Theorem 4], the left-invariant GCS corresponds to a real Lie subalgebra $\mathfrak{s} \subset \mathfrak{g}$ such that $\mathfrak{s} \cong T_{id}\mathscr{S}$ where $id \in G$ is the identity element. Since any (simply connected) nilpotent Lie group is solvable, $S = \exp(\mathfrak{s})$ is a closed simply connected Lie subgroup of G by [12, Section II]. Note that, by the closed subgroup theorem, S is an embedded submanifold of G and $T_{id}S = T_{id}\mathscr{S}$. Note that

$$TG \cong G \times \mathfrak{g}$$
 and $T\mathscr{S} \cong G \times \mathfrak{s}$.

Thus any leaf of \mathscr{S} is diffeomorphic to S via the left multiplication map. This implies that G is foliated by the left cosets of S, that is, the leaf space G/\mathscr{S} is G/S. Since S is closed, G/S is a smooth homogeneous manifold such that the quotient map $\pi_S : G \longrightarrow$ G/S is a smooth submersion.

Contractibily of G also implies that $\mathcal{N} \cong G \times \mathbb{R}^{2k}$. Let \langle , \rangle be an inner product on \mathbb{R}^{2k} . Consider the metric \langle , \rangle' on $G \times \mathbb{R}^{2k}$ defined as

$$\langle (g, v), (h, w) \rangle' = \langle v, w \rangle$$
 for all $(g, v), (h, w) \in G \times \mathbb{R}^{2k}$

Note that \langle , \rangle' is *G*-invariant. Then there exists a left-invariant metric, say *h* on \mathcal{N} such that (\mathcal{N}, h) is isometric to $(G \times \mathbb{R}^{2k}, \langle , \rangle')$. This *h* is a left-invariant transverse metric on *G*.

Hence, we have established the following result.

Theorem 14.1. Let G be a simply connected nilpotent Lie group with \mathfrak{g} as its real lie algebra. Suppose G has a left-invariant GCS. Let \mathscr{S} be the foliation induced by the GCS. Then, the following hold.

- (1) All leaves of \mathscr{S} are diffeomorphic to the leaf through the identity element of G.
- (2) S is a Riemannian foliation. In particular, G admits a transverse left-invariant metric.
- (3) G is foliated by the left cosets of S where $S \subset G$ is a closed simply connected Lie subgroup. The leaf space G/\mathscr{S} is the homogeneous manifold G/S.

Let $\Gamma \subset G$ be a maximal lattice (that is, cocompact, discrete subgroup). Malcev (cf. [23]) showed that such a lattice exists if and only if \mathfrak{g} has rational structure constants in some basis. Let $M^{2n} = \Gamma \setminus G$ be a nilmanifold with a left-invariant GCS. Using [10, Theorem 3.1], we can say that this left-invariant GCS is generalized Calabi-Yau. This GCS on M is induced from a left-invariant GCS on G. Let ρ be a global trivialization for the canonical line bundle of the left-invariant GCS on G as defined in (14.1). It also induces a global trivialization for the canonical line bundle of the canonical line bundle of the left-invariant GCS on M and S_M be the left form \mathcal{S}_M be the induced foliation corresponding to this GCS on M and S_M be the left form \mathcal{S}_M , that is, $\mathscr{S}_M = \Gamma \setminus \mathscr{S}$.

Now, the quotient map $\pi_{\Gamma} : G \longrightarrow M$ is a principal Γ -bundle as well as a covering map. It induces a principal $(S \cap \Gamma)$ -bundle $\pi_{\Gamma}|_S : S \longrightarrow S_M$ and so the fundamental group $\pi_1(S_M) = S \cap \Gamma$. Therefore, we can identify $S_M = (S \cap \Gamma) \setminus S$. Note that $\pi_{\Gamma}^{-1}(S_M) = \Gamma S$. By [26, Theorem 1.13], $S \cap \Gamma$ is a maximal lattice in S if and only if ΓS is closed. Thus, $S_M = (S \cap \Gamma) \setminus S \subset M$ is a compact leaf if and only if ΓS is closed. The transverse left-invariant metric on G (see Theorem 14.1), is preserved by Γ -action. Therefore, it induces a transverse metric on M. This implies that \mathscr{S}_M is a Riemannian foliation.

Consider the natural left Γ -action on G/S defined as $\eta \cdot gS = (\eta g)S$ and its quotient space $\widehat{M} := \Gamma \backslash G/S$ with the quotient topology such that $\widehat{\pi} : G/S \longrightarrow \widehat{M}$ is continuous. Note that this map is also open. So, we have the following diagram,



where M/\mathscr{S}_M is the leaf space and $\tilde{\pi}$ is the quotient map as defined in (7.3). We will use \tilde{S}_x to denote the leaf through $x \in M$. Let $g \in G$ and consider the map

$$\Phi: M/\mathscr{S}_M \longrightarrow \widehat{M} \quad \text{defined as} \quad \Phi(\widetilde{S}_{\pi_{\Gamma}(g)}) = \widehat{\pi}(\pi_S(g)).$$
 (14.2)

Let $g, g' \in G$ such that $\pi_{\Gamma}(g)$ and $\pi_{\Gamma}(g')$ are in the same leaf, that is, $\tilde{S}_{\pi_{\Gamma}(g)} = \tilde{S}_{\pi_{\Gamma}(g')}$. To show Φ is well-defined, we need to show that $\hat{\pi}(\pi_S(g)) = \hat{\pi}(\pi_S(g'))$.

Let $\gamma : [0,1] \longrightarrow \tilde{S}_{\pi_{\Gamma}(g)}$ be a path such that $\gamma(0) = \pi_{\Gamma}(g)$ and $\gamma(1) = \pi_{\Gamma}(g')$. Since G is the universal cover of M, the path γ lifts to a unique path $\tilde{\gamma}$ such that $\tilde{\gamma}(0) = g$ and $\tilde{\gamma}(1) = g''$ with $\pi_{\Gamma}(g') = \pi_{\Gamma}(g'')$. Now the path $\tilde{\gamma}$ is contained in one of the connected components of $\pi_{\Gamma}^{-1}(\tilde{S}_{\pi_{\Gamma}(g)})$, which is a leaf of \mathscr{S} , say, $\tilde{g}S$ for some $\tilde{g} \in G$, such that $\pi_{\Gamma}|_{\tilde{g}S} : \tilde{g}S \longrightarrow \tilde{S}_{\pi_{\Gamma}(g)}$ is a universal covering map. So, we get the following commutative diagram,



where *i* is inclusion and \tilde{i} is injective immersion. Since $g, g'' \in \tilde{g}S$, we have $\pi_S(g) = \pi_S(g'')$. Now g' and g'' are in the same fiber of the universal covering map π_{Γ} , and as $\pi_1(M) = \Gamma$, there exists $\eta \in \Gamma$ such that $\eta \cdot g'' = g'$. Note that Γ preserves the foliation \mathscr{S} and so, $\pi_S(\eta \cdot g'') = \eta \cdot \pi_S(g'')$. Therefore, we can see that $\pi_S(g') = \eta \cdot \pi_S(g)$ which implies that $\hat{\pi}(\pi_S(g)) = \hat{\pi}(\pi_S(g'))$. Hence, the map Φ is well defined.

Now define the inverse of Φ as

$$\Phi^{-1}\left(\widehat{\pi}(\pi_S(g))\right) = \widetilde{S}_{\pi_{\Gamma}(g)}.$$

We need to show that Φ^{-1} is well-defined. For that, let $g, g' \in G$ with the condition that $\widehat{\pi}(\pi_S(g)) = \widehat{\pi}(\pi_S(g'))$. It is enough to show that $\widetilde{S}_{\pi_{\Gamma}(g)} = \widetilde{S}_{\pi_{\Gamma}(g')}$. The given condition on $\pi_S(g)$ and $\pi_S(g')$ implies that there exists $\eta \in \Gamma$ such that

$$\pi_{S}(g) = \eta \cdot \pi_{S}(g') = \pi_{S}(\eta \cdot g').$$

Then, there exists $\tilde{g} \in G$ such that $g, \eta \cdot g' \in \tilde{g}S$, that is, they belong to the same leaf of \mathscr{S} . This implies that $\pi_{\Gamma}(g) = \pi_{\Gamma}(\eta \cdot g') = \pi_{\Gamma}(g')$. Hence $\tilde{S}_{\pi_{\Gamma}(g)} = \tilde{S}_{\pi_{\Gamma}(g')}$. So Φ^{-1} is well-defined.

Note that $\pi_{\Gamma}, \tilde{\pi}, \pi_S$ and $\hat{\pi}$ are open maps and we have the following commutative diagram:



This implies both Φ and Φ^{-1} are continuous and so, Φ is a homeomorphism.

Let $x, y \in \widehat{M}$. There exist $g, g' \in G$ such that $\widehat{\pi}^{-1}(x) = \Gamma gS$ and $\widehat{\pi}^{-1}(y) = \Gamma g'S$. Now the map $\Gamma gS \longrightarrow \Gamma g'S$ defined as $\eta gs \longmapsto \eta g's$ is a diffeomorphism. In particular, both orbits are diffeomorphic to ΓS . Suppose ΓS is closed. Set

$$\ker(\widehat{\pi}) := \left\{ (gS, g'S) \,|\, \widehat{\pi}(gS) = \widehat{\pi}(g'S) \right\} \subset G/S \times G/S \,.$$

To show \widehat{M} is Hausdroff, it is enough to show that ker $(\widehat{\pi})$ is closed, because $\widehat{\pi}$ is an open surjection.

Let $\{(g_n^1S, g_n^2S)\}_n \in \ker(\widehat{\pi})$ be a sequence converging to (g^1S, g^2S) . Then $\{g_n^jS\}_n$ is converging to g^jS for j = 1, 2. By the assumption on $\{g_n^jS\}_n$ (j = 1, 2), they belong to the same Γ -orbit, in other words, there exist \widetilde{g} such that $g_n^jS \in \Gamma \widetilde{g}S$ (j = 1, 2). Since any two Γ -orbits are diffeomorphic, and ΓS is closed, $\Gamma \widetilde{g}S$ is also closed. This implies that $g^jS \in \Gamma \widetilde{g}S$ for j = 1, 2. Therefore, $\widehat{\pi}(g^1S) = \widehat{\pi}(g^2S)$. This implies $(g^1S, g^2S) \in \ker(\widehat{\pi})$ and $\ker(\widehat{\pi})$ is closed. Hence, M/\mathscr{S}_M is Hausdroff. So, each leaf is closed as well as compact in M. Since \mathscr{S}_M is a Riemannian foliation, the holonomy group of any leaf is finite, and M/\mathscr{S}_M is a smooth orbifold. Hence we have proved the following.

Theorem 14.2. Let $M = \Gamma \setminus G$ be a nilmanifold with a left-invariant GCS. Let \mathscr{S}_M be the induced foliation. Then, the following hold.

- (1) \mathscr{S}_M is a Riemannian foliation.
- (2) M/\mathscr{S}_M is homeomorphic to $\Gamma \backslash G/S$ where $S \subset G$ is a closed simply connected Lie subgroup.
- (3) M/\mathscr{S}_M is a compact smooth orbifold $\iff \Gamma S$ is closed $\iff (S \cap \Gamma) \setminus S$ is compact.

Example 14.3. Consider the complex Heisenberg group

$$G = \left\{ \begin{pmatrix} 1 & z_1 & z_3 \\ 0 & 1 & z_2 \\ 0 & 0 & 1 \end{pmatrix} \mid z_j \in \mathbb{C} \ (j = 1, 2, 3) \right\}.$$
G is a 6-dimensional simply connected nilpotent lie group. Consider a maximal lattice $\Gamma \subset G$ defined as

$$\Gamma = \left\{ \begin{pmatrix} 1 & a_1 & a_3 \\ 0 & 1 & a_2 \\ 0 & 0 & 1 \end{pmatrix} \middle| a_j \in \mathbb{Z} \oplus i\mathbb{Z} (j = 1, 2, 3) \right\}.$$

Then, Γ acts on G by left multiplication and the corresponding nilmanifold $M = \Gamma \setminus G$ is known as Iwasawa manifold. Let \mathfrak{g} be the real lie algebra of G. Choose a basis $\{e_1, e_2, \ldots, e_6\} \in \mathfrak{g}^*$ by setting

$$dz_1 = e_1 + ie_2$$
, $dz_2 = e_3 + ie_4$, and $z_1 dz_2 - dz_3 = e_5 + ie_6$.

These real 1-forms are pullbacks of the corresponding 1-forms on M, which we denote by the same symbols. They satisfy the following equations:

$$de_j = 0 \quad \forall \ 1 \le j \le 4$$
.
 $de_5 = e_{13} + e_{42} \quad \text{and} \quad de_6 = e_{14} + e_{23}$.

Here, we make use of the notation $e_{jl} = e_j \wedge e_l$ for all $j, l \in \{1, \ldots, 6\}$.

Consider the mixed complex form

$$\rho = e^{i(e_{56})}(e_1 + ie_2) \wedge (e_3 + ie_4) \quad \text{on } M.$$

Note that $de_5 \wedge de_6 = 0$ and $(e_1 + ie_2) \wedge (e_3 + ie_4) = de_5 + ide_6$. Then, we have,

$$d\rho = e^{i(e_{56})} \wedge d(ie_{56}) \wedge (e_1 + ie_2) \wedge (e_3 + ie_4)$$

= $e^{i(e_{56})} \wedge d(ie_{56}) \wedge (de_5 + ide_6)$
= $-e^{i(e_{56})} \wedge (e_6 + ie_5) \wedge de_5 \wedge de_6$
= 0,

and

$$e_{56} \wedge (e_1 + ie_2) \wedge (e_3 + ie_4) \wedge (e_1 - ie_2) \wedge (e_3 - ie_4) = e_{56} \wedge (de_5 + ide_6) \wedge (de_5 - ide_6)$$

= $-ie_{56} \wedge de_5 \wedge de_6$
\$\neq 0.\$

By [14, Theorem 3.38, Theorem 4.8], M admits a type 2 strong generalized Calabi-Yau structure whose canonical line bundle is generated by ρ . It is straightforward to see that ρ , when considered as a mixed form on G, gives a left-invariant GCS on G which is a strong generalized Calabi-Yau structure.

Let $f: G \longrightarrow \mathbb{C}^2$ be the natural projection defined as

$$\tilde{\pi}\begin{pmatrix} 1 & z_1 & z_3 \\ 0 & 1 & z_2 \\ 0 & 0 & 1 \end{pmatrix} = (z_1, z_2).$$

One can see that Γ -acts on (z_1, z_2) via left translation by $\mathbb{Z} \oplus i\mathbb{Z}$. This shows that f induces a surjective submersion

$$\tilde{f}: M \longrightarrow \bigoplus_{j=1}^{2} \mathbb{C}/\mathbb{Z} \oplus i\mathbb{Z} \cong \mathbb{T}^{2} \times \mathbb{T}^{2},$$

that satisfies the following commutative diagram,



where $\mathbb{C}^2 \longrightarrow \mathbb{T}^2 \times \mathbb{T}^2$ is the natural quotient map. So, there exist $\theta_1, \theta_2 \in \Omega^2(\mathbb{T}^2 \times \mathbb{T}^2, \mathbb{C})$ such that $\tilde{f}^*(\theta_1) = e_1 + ie_2$ and $\tilde{f}^*(\theta_2) = e_3 + ie_4$. Now, each fiber of this submersion is diffeomorphic to $\mathbb{C}/\mathbb{Z} \oplus i\mathbb{Z} \cong \mathbb{T}^2$. Therefore, the foliation induced by the strong generalized Calabi-Yau structure on M is simple with leaf space $\mathbb{T}^2 \times \mathbb{T}^2$ and with the fibers as leaves.

Let M be a type k regular GC manifold such that the leaf space M/\mathscr{S} of the induced foliation \mathscr{S} is a smooth manifold. Then $\mathscr{M} = M/\mathscr{S}$, as defined in (7.2), becomes a complex manifold of complex dimension k and the quotient map $\tilde{\pi} : M \longrightarrow \mathscr{M}$, as defined in (7.3), becomes a smooth surjective submersion. In particular, $\tilde{\pi}$ is an open map.

For any open set $V \subseteq M$, consider the map $\tilde{\pi}^{\#} : \tilde{\pi}^{-1}\mathcal{O}_{\mathcal{M}} \longrightarrow \mathcal{O}_{M}$ defined as

$$\tilde{\pi}^{\#}(f) = f \circ \tilde{\pi} \quad \text{for } f \in \mathcal{O}_{\mathscr{M}}(\tilde{\pi}(V)),$$
(14.3)

where $\mathcal{O}_{\mathscr{M}}$ is the sheaf of holomorphic functions. To show $\tilde{\pi}^{\#}$ is an isomorphism, it is enough to show $\tilde{\pi}^{\#}_x : (\tilde{\pi}^{-1}\mathcal{O}_{\mathscr{M}})_x \longrightarrow (\mathcal{O}_M)_x$ is an isomorphism for $x \in M$.

Let $x \in M$ and set $y = \tilde{\pi}(x)$. Let $\{U, \phi\}$ be a co-ordinate chart around y in \mathcal{M} , and let $S_x = \tilde{\pi}^{-1}(y)$ be the fiber (leaf) over y. Then, choosing U sufficiently small, we the following commutative diagram by Theorem 7.3,



where $\tilde{\phi}$ is a GH homomorphism, $U' \subset \mathbb{C}^k$ is an open set, and \tilde{S}_x is the universal cover of S_x . Note that \mathcal{O}_V is isomorphic to $\tilde{\phi}^{-1}\mathcal{O}_{S_x \times \mathbb{C}^k}$ via $\tilde{\phi}^{\#}$, defined in a similar manner as in (14.3), and $\mathcal{O}_{S_x \times U'} = \operatorname{Pr}_2^{-1} \mathcal{O}_{U'}$. Using commutativity of the diagram and the fact that \mathcal{O}_U is isomorphic to $\phi^{-1}\mathcal{O}_{U'}$ via $\phi^{\#}$, defined similarly as in (14.3), we can show that $\tilde{\pi}^{-1}\mathcal{O}_U$ is isomorphic to \mathcal{O}_V via $\tilde{\pi}^{\#}$. Therefore, $\tilde{\pi}_x^{\#}$ is isomorphism and so is $\tilde{\pi}^{\#}$. Similarly one can show that $\tilde{\pi}^{\#}$ is also an isomorphism even when we replace \mathcal{O}_M by F_M , that is,

$$\tilde{\pi}^{\#}: \tilde{\pi}^{-1}C^{\infty}_{\mathscr{M}} \longrightarrow F_{\mathscr{M}} \quad \text{is an isomorphism}.$$
(14.4)

Let GM and G^*M be the GH tangent and GH cotangent bundle of M, as defined in (5.3) and (5.1), respectively. Let $\{U_\alpha\}$ be a coordinate atlas of \mathscr{M} such that $\tilde{\pi}^{-1}U_\alpha \cong \tilde{S}_\alpha \times U'_\alpha$ via a GH homeomorphism for some leaf S_α and $U'_\alpha \subset \mathbb{C}^k$ open set where \tilde{S}_α is the universal cover of S_α . Note that,

$$F_M(G^*M)|_{\tilde{\pi}^{-1}U_\alpha} = \operatorname{Span}_{F_M(\tilde{\pi}^{-1}U_\alpha)} \{ dz_1, \dots, dz_k \}$$

where z_j $(1 \le j \le k)$ are holomorphic coordinates on U'_{α} . Then (14.4) naturally induces an isomorphism

$$\tilde{\tilde{\pi}}^{\#}|_{U_{\alpha}}: C^{\infty}_{\mathscr{M}}(T^{1,0*}\mathscr{M})|_{U_{\alpha}} \longrightarrow F_{M}(G^{*}M)|_{\tilde{\pi}^{-1}U_{\alpha}},$$

which gives rise to a sheaf isomorphism

$$\tilde{\tilde{\pi}}^{\#}: \tilde{\pi}^{-1}C^{\infty}_{\mathscr{M}}(T^{1,0*}\mathscr{M}) \longrightarrow F_M(G^*M),$$

where $T^{1,0}\mathcal{M}$ is the holomorphic tangent bundle of \mathcal{M} . Replacing $F_M(G^*M)$ by $F_M(\overline{G^*M})$, one can show, similarly, that

$$\tilde{\tilde{\pi}}^{\#}: \tilde{\pi}^{-1}C^{\infty}_{\mathscr{M}}(T^{0,1*}\mathscr{M}) \longrightarrow F_M(\overline{G^*M}).$$

Also, similarly, we can show that $F_M(GM) \cong \tilde{\pi}^{-1}C^{\infty}_{\mathscr{M}}(T^{1,0}\mathscr{M})$ because $F_M(GM) = Hom_{F_M}(F_M(G^*M), F_M)$.

This shows that, for $l, p, q \geq 0$, A^l (respectively, $A^{p,q}$), as defined in (8.4), is isomorphic to $\tilde{\pi}^{-1}(\Omega^l_{\mathscr{M}})$ (respectively, $\tilde{\pi}^{-1}(\Omega^{p,q}_{\mathscr{M}})$) where $\Omega^l_{\mathscr{M}}$ is the sheaf of \mathbb{C} -valued smooth *l*-forms. In particular, The map $\tilde{\pi}^{\#}$ induces the pullback map $\tilde{\pi}^*$ from $\Omega^l(\mathscr{M}, \mathbb{C})$ (respectively, $\Omega^{p,q}(\mathscr{M}, \mathbb{C})$) to $A^l(M)$ (respectively, $A^{p,q}(M)$) which is an isomorphism of \mathbb{C} -vector spaces. By the definitions of D and d_L (see (8.7) and (8.11)), we have the following commutative diagrams.

This shows that we have surjective homomorphisms at the level of deRham cohomology and Dolbeault cohomology, respectively:

$$\tilde{\pi}^*: H^l_{dR}(\mathscr{M}, \mathbb{C}) \longrightarrow H^l_D(M) \quad \text{and} \quad \tilde{\pi}^*: H^{p,q}_{\overline{\partial}}(\mathscr{M}) \longrightarrow H^{p,q}_{d_L}(M) \,.$$

Since $\tilde{\pi}$ is a submersion, $\tilde{\pi}^*$ is one-to-one. Hence, $\tilde{\pi}^*$ is an isomorphism of \mathbb{C} -vector spaces. We summarize our results as follows.

Theorem 14.4. Let M be a regular GC manifold such that the leaf space of the induced foliation is a smooth manifold \mathscr{M} . Let GM and G^*M be the GH tangent and GHcotangent bundle of M. Let $\tilde{\pi} : M \longrightarrow \mathscr{M}$ be the quotient map, and let $T^{1,0}_{\mathscr{M}}$ be the sheaf holomorphic sections of the holomorphic tangent bundle of \mathscr{M} . Then the following hold.

(1) $F_M \cong \tilde{\pi}^{-1}C^{\infty}_{\mathscr{M}}$ and $\mathcal{O}_M \cong \tilde{\pi}^{-1}\mathcal{O}_{\mathscr{M}}$. (2) $F_M(GM) \cong \tilde{\pi}^{-1}C^{\infty}_{\mathscr{M}}(T^{1,0}\mathscr{M})$ and $F_M(G^*M) \cong \tilde{\pi}^{-1}C^{\infty}_{\mathscr{M}}(T^{1,0*}\mathscr{M})$. In particular, $GM \cong \tilde{\pi}^*T^{1,0}\mathscr{M}$ and $G^*M \cong \tilde{\pi}^*T^{1,0*}\mathscr{M}$. (3) $\mathcal{G}\mathbf{M} \cong \tilde{\pi}^{-1}T^{1,0}_{\mathscr{M}}$ and $\mathcal{G}^*\mathbf{M} \cong \tilde{\pi}^{-1}T^{1,0*}_{\mathscr{M}}$. (4) $H^l_{dR}(\mathscr{M}, \mathbb{C}) \cong H^l_D(M)$ and $H^{p,q}_{\overline{\partial}}(\mathscr{M}) \cong H^{p,q}_{d_L}(M)$.

Remark 14.5. Theorem 14.4 implies that the pullback of any holomorphic vector bundle on the leaf space is an SGH vector bundle of M. A natural question is whether all SGH vector bundles arise in this way. The following two examples demonstrate that this is not always the case.

Example 14.6. Let M_1 be a complex manifold and M_2 be a symplectic manifold. Consider the natural product GCS on $M_1 \times M_2$. Consider the SGH vector bundle $\bigotimes_i \operatorname{Pr}_i^* V_i$ over $M_1 \times M_2$, as defined in Example 3.14 where V_1 is a holomorphic vector bundle over M_1 and V_2 is flat vector bundle over M_2 . This bundle is not a pullback of a holomorphic vector bundle over M_1 unless V_2 is trivial.

Example 14.7. Let G be the Heisenberg group and $M = \Gamma \setminus G$ be the Iwasawa manifold with the left-invariant GCS as defined in Example 14.3. Let $\rho : \Gamma \longrightarrow GL_l(\mathbb{C})$ be a nontrivial (faithful) representation. Let $G \times_{\rho} \mathbb{C}^l$ be the SGH bundle over M as defined in Example 3.13. Let $S \cong \mathbb{T}^2$ be a leaf of the induced foliation. Considering $\pi_1(S) < \Gamma$, $(G \times_{\rho} \mathbb{C}^l)|_S$ is isomorphic to $\mathbb{R}^2 \times_{\rho'} \mathbb{C}^l$ where $\rho' = \rho|_{\pi_1(S)}$ is a non-trivial representation. If possible let, there exist a holomorphic vector bundle W over $\mathbb{T}^2 \times \mathbb{T}^2$ such that $\tilde{f}^*W = G \times_{\rho} \mathbb{C}^l$. But, then the restriction of \tilde{f}^*W to any of the fibers of \tilde{f} is a trivial bundle which is not possible as the fibers of \tilde{f} are the leaves of the induced foliation by the left-invariant GCS. Hence $G \times_{\rho} \mathbb{C}^l$ is an SGH vector bundle on M which is not a pullback of any holomorphic vector bundle on $\mathbb{T}^2 \times \mathbb{T}^2$.

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