SOME REMARKS ON TOPOLOGICAL
4d-GRAVITY

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Abstract

We show that the method of S. Wu to study topological 4d-gravity can be understood within a now standard method designed to produce equivariant cohomology classes. Next, this general framework is applied to produce some observables of the topological 4d-gravity.
1 Introduction.

Since its appearance in 1988 in a famous article of E. Witten [W88], Topological Field Theories have played an important role in theoretical physics as well as in mathematics. Actually, the 1988 article gave a prototype of Topological Field Theories of cohomological type. Witten has recognized that these Cohomological Field Theories are related to Equivariant Cohomology and more precisely to the so-called Cartan model of Equivariant Cohomology.

Although Cohomological Field Theories can be described independently of which model is used for Equivariant Cohomology, the construction by J. Kalkman ([K93]) of the so-called intermediate model ([STW94]) is of considerable technical help. In [STW94], Topological Yang-Mills ([W88, BS88, AJ90]) and Topological 2d Gravity ([BS91]) where studied from this point of view. In [BT97], new representatives of the Thom class of a vector bundle where produced using this general framework.

S. Wu [Wu93] explained the role of the universal bundle in 4d Gravity, and exhibited some observables of the corresponding topological model. We shall explained here how his method can be deduced from the general approach of [STW94] and which observables are obtained.

2 From the Intermediate to the Weil Model of equivariant cohomology.

In [STW94] it was explained how one can generate representatives of equivariant cohomology classes using an idea of [BGV91] which benefits from J. Kalkman's construction ([K93]) as follows: let us assume that $\mathcal{M}$ is a smooth manifold with smooth $\mathcal{G}$-action for some connected Lie group $\mathcal{G}$ (with Lie algebra $\text{Lie}\mathcal{G}$). Let $d_M$, $i_M$, $l_M$ be the standard exterior derivative, inner product and Lie derivative on $\mathcal{M}$. The action of $\mathcal{G}$ induces an action of $\text{Lie}\mathcal{G}$, and to any $\lambda \in \text{Lie}\mathcal{G}$, there corresponds a so-called fundamental vector field $\lambda_M$ on $\mathcal{M}$. The space of forms on $\mathcal{M}$ is denoted by $\Omega(\mathcal{M})$, and its basic elements are those annihilated both by $i_M(\lambda)$ and $l_M(\lambda)$, for any $\lambda \in \text{Lie}\mathcal{G}$. We recall that $l_M = [d_M, i_M]_+$.

The Weil algebra $(\mathcal{W}(\mathcal{G}), d_W, i_W, l_W)$ of $\mathcal{G}$, is the graded differential algebra generated by the "connection $\omega$" and its "curvature $\Omega$":

\begin{align}
    d_W \omega &= \Omega - \frac{1}{2} [\omega, \omega] \\
    d_W \Omega &= -[\omega, \Omega] \\
    i_W(\lambda) \omega &= \lambda
\end{align}

1
\begin{align*}
 i_W(\lambda)\Omega &= 0 \\
 l_W(\lambda)\omega &= -[\lambda,\omega] \\
 i_W(\lambda)\Omega &= -[\lambda,\Omega]
\end{align*}

for any $\lambda \in \text{Lie}\mathcal{G}$.

Then, the equivariant cohomology for the action of $\mathcal{G}$ on $\mathcal{M}$ is the basic cohomology of the graded differential algebra $(W(\mathcal{G}) \otimes \Omega(\mathcal{M}), d_W + d_M, i_W + i_M, l_W + l_M)$. It generates the so-called Weil model of equivariant cohomology.

Now let us consider another Lie group $\mathcal{H}$ such that $\mathcal{M}$ is the base space of some principal $\mathcal{H}$-bundle $\mathcal{P}(\mathcal{M}, \mathcal{H})$ on which the action of $\mathcal{G}$ can be lifted. This bundle is also equipped with standard differential operations: $d_P, i_P, l_P$. Then, some equivariant cohomology classes can be represented as follows: consider a $\mathcal{G}$-invariant $\mathcal{H}$-connection $\Gamma$ on $\mathcal{P}$. Extend $\Gamma$ to $W(\mathcal{G}) \otimes \Omega(\mathcal{M})$, still denoting it $\Gamma$. Since $\Gamma$ does not depend on $\omega$, it fulfills:

\begin{align*}
 i_W(\lambda)\Gamma &= 0 \\
 (l_W + l_P)(\lambda)\Gamma &= 0
\end{align*}

for any $\lambda \in \text{Lie}\mathcal{G}$. That expresses the basicity of $\Gamma$ in the so-called Intermediate model of equivariant cohomology. In this model, the exterior derivative reads:

\[ D_{\text{int}} = d_W + d_P + l_P(\omega) - i_P(\Omega) \]

so that:

\[ D_{\text{int}}\Gamma = d_P\Gamma - i_P(\Omega)\Gamma \]

and the Equivariant curvature of $\Gamma$ in the intermediate model reads:

\[ R_{\text{int}}^{eq}(\Gamma, \omega, \Omega) = D_{\text{int}}\Gamma + \frac{1}{2} [\Gamma, \Gamma] \]

It satisfies:

\begin{align*}
 D_{\text{int}}R_{\text{int}}^{eq} &= [R_{\text{int}}^{eq}, \Gamma] \\
 i_W(\lambda)R_{\text{int}}^{eq} &= 0 \\
 (l_W + l_P)(\lambda)R_{\text{int}}^{eq} &= 0
\end{align*}

The $\mathcal{H}$-fibration is eliminated by considering symmetric $\mathcal{H}$-invariant polynomials $I_{\text{int}}^{eq} = I(R_{\text{int}}^{eq})$. 

2
To go to the more usual Weil Model, we use the Kalkman differential algebra isomorphism \( \exp \{ i_P(\omega) \} \), thus obtaining:

\[
(d_W + d_P) I^e_W = 0 \quad (15)
\]

\[
(i_W + i_P)(\lambda) I^e_W = 0 \quad (16)
\]

\[
(l_W + l_P)(\lambda) I^e_W = 0 \quad (17)
\]

where \( I^e_W = \exp \{ i_P(\omega) \} I^e_{int} \). Now since the \( H \)-fibration has disappeared, \( I^e_W \) lies in \( \mathcal{W}(\mathcal{G}) \otimes \Omega(\mathcal{M}) \). Under the assumption that \( \mathcal{M} \) is a principal \( \mathcal{M} \)-bundle over \( \mathcal{M}/\mathcal{G} \), we can replace \( \omega \) and \( \Omega \) by a \( \mathcal{G} \)-connection \( \theta \) and its curvature \( \Theta \) on \( \mathcal{M} \). Cartan’s theorem 3 guarantees that our new representative gives a representative of the same equivariant cohomology class ([C50], [STW94]). Still denoting this representative by \( I^e_W \), we verify that:

\[
d_M I^e_W = 0 \quad (18)
\]

\[
i_M(\lambda) I^e_W = 0 \quad (19)
\]

\[
l_M(\lambda) I^e_W = 0 \quad (20)
\]

Now, we are ready to use this method in topological 4d-gravity.

3 Wu’s construction ([Wu93]) in Topological 4d Gravity.

Let \( \Sigma \) be a 4d smooth manifold. The fundamental objects in \( Gr^{top}_4 \) are the metrics of \( \Sigma \), and the generators of the Weil algebra of \( Diff_0(\Sigma) \) the connected component of the diffeomorphism group of \( \Sigma \). The structure equations then read:

\[
s^{top} g = \Psi + L^{top}(\omega)g \quad (21)
\]

\[
s^{top} \Psi = -L^{top}(\Omega)g + L^{top}(\omega)\Psi \quad (22)
\]

\[
s^{top} \omega = \Omega - \frac{1}{2}[\omega, \omega] \quad (23)
\]

\[
s^{top} \Omega = -[\omega, \Omega] \quad (24)
\]

Let us note that the form of these structure equations is universal (i.e. independent of the model we choose). Now let us apply the precepts of the previous section. The group of diffeomorphisms of \( \Sigma \) plays the role of the gauge group \( \mathcal{G} \) over \( Met(\Sigma) \). The \( H \)-fibration
is obtained by considering the frame bundle over $\Sigma$, $F(\Sigma)$, and our final principal $GL(4, \mathbb{R})$-bundle $P$ is just $Met(\Sigma) \times F(\Sigma)$. The $Diff(\Sigma)$-invariant $GL(4, \mathbb{R})$-connection $\Gamma$ on $Met(\Sigma) \times F(\Sigma)$ is given by:

$$\Gamma^\lambda_{\mu} = \Gamma^{LC}(g)^\lambda_{\mu} + \frac{1}{2} g^{\lambda \nu} \delta g_{\nu \mu}$$

where $\Gamma^{LC}(g)$ is the Levi-Civita connection of $g \in Met(\Sigma)$, and $\delta$ is the exterior derivative on $Met(\Sigma)$ ([BS91, DV]).

This $GL(4, \mathbb{R})$-connection is used in the Intermediate Model. Before going any further, let us notice that in the Weil model, this connection reads:

$$\tilde{\Gamma}^\lambda_{\mu} = \Gamma^\lambda_{\mu} - (i_P(\Omega)\Gamma)^\lambda_{\mu}$$

which is comparable with (2.5) in [Wu93]. Now, the Intermediate curvature:

$$R^eq_{int}(\Gamma, \omega, \Omega) = D_{int}\Gamma + \frac{1}{2} [\Gamma, \Gamma]$$

(27)

gives the corresponding Weil curvature:

$$R^eq_W(\Gamma, \omega, \Omega) = \exp \{ i_P(\omega) \} R^eq_{int}(\Gamma, \omega, \Omega) = (d_W + d_P)\tilde{\Gamma} + \frac{1}{2} [\tilde{\Gamma}, \tilde{\Gamma}]$$

(28)

which is of the form (2.6) of [Wu93].

Now, let us have a look at the observables.

4 Some Observables for Topological 4d Gravity.

In order to generate observables of the theory, we first eliminate the $GL(4, \mathbb{R})$-fibration. As explained in section 2 this is achieved by considering symmetric $GL(4, \mathbb{R})$-invariant polynomials. The Euler class and the Pontrjagin classes generated by $R^eq_W$ are such polynomials ([KN63]). Actually, only the first Pontrjagin class is relevant. Up to normalization factors, those two cohomology classes are given by:

$$E^eq_W = \frac{\varepsilon^{\mu \nu \rho \sigma}}{\sqrt{g}} g_{\nu \lambda} g_{\sigma \chi} (R^eq_W)_{\mu}^{\lambda} \wedge (R^eq_W)_{\rho}^{\chi}$$

(29)

$$P^eq_W = (\delta^\mu_{\lambda} \delta^\rho_{\chi} - \delta^\mu_{\chi} \delta^\rho_{\lambda}) (R^eq_W)_{\mu}^{\lambda} \wedge (R^eq_W)_{\rho}^{\chi}$$

(30)

1Note that $F(\Sigma)$ is the principal bundle associated to the tangent vector bundle $T\Sigma$ of $\Sigma$

2The zeroth class is trivially 1 while the second (and highest) class is the square of the Euler class.
and decompose into five terms:

\[ E_W^{eq} = Q_0^4 + Q_1^3 + Q_2^2 + Q_3^1 + Q_4^0 \]  
\[ P_W^{eq} = G_0^4 + G_1^3 + G_2^2 + G_3^1 + G_4^0 \]  

where the upper index refers to the form degree on \( \text{Met}(\Sigma) \) while the lower one refers to the form degree on \( \Sigma \). These expressions are to be compared with (2.9) of [Wu93]. Observables extracted from monomials \((E_W^{eq})^n (P_W^{eq})^n\):

\[
(E_W^{eq})^m (P_W^{eq})^n = V_0^{4(m+n)} + V_1^{4(m+n)-1} + V_2^{4(m+n)-2} + V_3^{4(m+n)-3} + V_4^{4(m+n)-4}
\]

with:

\[
V_0^{4(m+n)} = (Q_0^4)^m (G_0^4)^n
\]

\[
V_1^{4(m+n)-1} = n (Q_0^4)^m (G_0^4)^{n-1} G_1^3 + m (Q_0^4)^{m-1} Q_1^3 (G_0^4)^n
\]

\[
V_2^{4(m+n)-2} = n (Q_0^4)^m (G_0^4)^{n-1} G_2^2 + \frac{n(n-1)}{2} (Q_0^4)^m (G_0^4)^{n-2} (G_1^3) + m (Q_0^4)^{m-1} Q_1^3 (G_0^4)^n
\]

\[
+ \frac{m(m-1)}{2} (Q_0^4)^{m-2} Q_2^2 Q_1^3 (G_0^4)^n
\]

\[
V_3^{4(m+n)-3} = n (Q_0^4)^m (G_0^4)^{n-1} G_3^1 + \frac{n(n-1)}{2} (Q_0^4)^m (G_0^4)^{n-2} G_2^2 G_1^3
\]

\[
+ \frac{n(n-1)(n-2)}{6} (Q_0^4)^m (G_0^4)^{n-3} (G_1^3)^3
\]

\[
+ mn (Q_0^4)^{m-1} Q_1^3 (G_0^4)^{n-1} G_2^2 + \frac{n(n-1)}{2} (Q_0^4)^{m-1} Q_1^3 (G_0^4)^{n-2} (G_1^3)^2
\]

\[
+ mn (Q_0^4)^{m-1} Q_2^2 (G_0^4)^{n-1} G_1^3 + n \frac{m(m-1)}{2} (Q_0^4)^{m-2} (G_1^3)^2 (G_0^4)^{n-1} G_1^3
\]

\[
+ mn (Q_0^4)^{m-1} Q_3^1 (G_0^4)^n + \frac{m(m-1)}{2} (Q_0^4)^{m-2} Q_2^2 Q_1^3 (G_0^4)^n
\]

\[
+ \frac{m(m-1)(m-2)}{6} (Q_0^4)^{m-3} (Q_1^3)^3 (G_0^4)^n
\]
where I over cycles on Σ to obtain forms on Met
The corresponding forms fulfill the ”descent” equations:

\[
\begin{align*}
V^4_{4(m+n)-4} &= n(Q_0^4)^m (G^4_0)^{n-1} G^0_4 + \frac{n(n-1)}{2} (Q_0^4)^m (G^4_0)^{n-2} \left( (G^2_2)^2 + G^3_3 G^1_3 \right) \\
&+ \frac{n(n-1)(n-2)}{6} (Q_0^4)^m (G^4_0)^{n-3} (G^1_1)^2 G^2_2 \\
&+ \frac{n(n-1)(n-2)(n-3)}{24} (Q_0^4)^m (G^4_0)^{n-4} (G^1_1)^4 \\
&+ mn (Q_0^4)^{m-1} Q_1^1 (G^4_0)^{n-1} G^1_3 + m \frac{n(n-1)}{2} (Q_0^4)^{m-1} Q_1^1 (G^4_0)^{n-2} G^2_3 G^1_1 \\
&+ m \frac{n(n-1)(n-2)}{6} (Q_0^4)^{m-1} Q_1^1 (G^4_0)^{n-3} (G^1_1)^3 \\
&+ mn (Q_0^4)^{m-1} Q_2^2 (G^4_0)^{n-1} G^2_2 + m \frac{n(n-1)}{2} (Q_0^4)^{m-1} Q_2^2 (G^4_0)^{n-2} (G^1_1)^2 \\
&+ n \frac{m(m-1)}{2} (Q_0^4)^{m-2} (G^1_1)^2 (G^4_0)^{n-1} G^2_2 \\
&+ \frac{mn(m-1)(n-1)}{4} (Q_0^4)^{m-2} (G^1_1)^2 (G^4_0)^{n-2} (G^1_1)^2 \\
&+ mn (Q_0^4)^{m-1} Q_3^3 (G^4_0)^{n-1} G^3_3 + n \frac{m(m-1)}{2} (Q_0^4)^{m-2} Q_3^3 (G^4_0)^{n-1} G^3_3 \\
&+ n \frac{m(m-1)(m-2)}{6} (Q_0^4)^{m-3} Q_1^1 (G^4_0)^{n-1} G^3_3 \\
&+ m (Q_0^4)^{m-1} Q^0_1 (G^4_0)^{n} + m \frac{m(m-1)}{2} (Q_0^4)^{m-2} \left( (Q^2_2)^2 + Q^3_1 Q^1_3 \right) (G^4_0)^{n} \\
&+ \frac{m(m-1)(m-2)}{6} (Q_0^4)^{m-3} (G^1_1)^2 Q^2_2 (G^4_0)^{n} \\
&+ \frac{m(m-1)(m-2)(m-3)}{24} (Q_0^4)^{m-4} (G^1_1)^4 (G^4_0)^{n}
\end{align*}
\]

Next, we replace \( \omega \) and \( \Omega \) by a \( Diff(\Sigma) \)-connection \( \theta \) and its curvature \( \Theta \) on Met(\( \Sigma \)). The corresponding forms fulfill the ”descent” equations:

\[
\begin{align*}
\delta V^4_{4n-p} + d_\Sigma V^4_{4n-p+1} &= 0 \\
\mathcal{I}(\lambda) V^4_{4n-p} + i_\Sigma(\lambda) V^4_{4n-p+1} &= 0 \\
\mathcal{L}(\lambda) V^4_{4n-p} + l_\Sigma(\lambda) V^4_{4n-p} &= 0
\end{align*}
\]

where \( \mathcal{I} \) and \( \mathcal{L} \) are the inner product and Lie derivative on Met(\( \Sigma \)). Finally, we integrate over cycles on \( \Sigma \) to obtain forms on Met(\( \Sigma \)) only:

\[
V^4_{4n-p} = \oint_{\gamma_p} V^4_{4n-p}
\]
Exactly as in the 2d gravity, only:

\[ V_{4n-4} = \int_{\Sigma} V_{4n-4} \]  (43)

defines an equivariant form on \( Met(\Sigma) \). This gives observables of \( Gr_{4}^{\text{top}} \), which are the analogs of the Mumford invariants appearing in \( Gr_{2}^{\text{top}} \).

An explicit expression of the Q’s and the G’s is given in appendix.

5 Conclusion.

All the work done above can be apply to higher dimensional gravity theory. Of course this also apply to Yang-Mills topological theory. Nevertheless, in this last case things are much simpler since the gauge group doesn’t act on the space-time manifold \( \Sigma \), while in Gravity theory the diffeomorphism group does.

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Appendix.

It was already shown in [STW94] that the Weil curvature takes the form:

\[ (R^{\text{eq}})_{\nu}^{\mu} = \left( R^{LC} - \imath_{\Sigma}(\omega)R^{LC} + \frac{i_{\Sigma}(\omega)i_{\Sigma}(\omega)}{2}R^{LC} + \frac{1}{2}D^{LC} \wedge \bar{\gamma} \right)_{\mu}^{\nu} 
\]

\[ -\frac{1}{2}i_{\Sigma}(\omega)D^{LC} \wedge \bar{\gamma} - \frac{1}{4}\bar{\psi}\bar{\psi} + \frac{1}{2}D^{LC} \wedge \bar{\Omega} \]  (44)

where:

\[ \bar{\gamma}_{\mu} = (\delta g_{\mu\nu} - L_{\Sigma}(\omega)g_{\mu\nu})dx^\mu = \bar{\gamma}_{\rho\mu}dx^\rho \]  (45)

\[ \bar{\psi}_{\mu} = g^{\mu\nu}(\delta g_{\rho\mu} - L_{\Sigma}(\omega)g_{\rho\mu}) = g^{\mu\nu}(\bar{\gamma}_{\rho\mu}) = (g^{-1}\bar{\gamma})^{\mu}_{\nu} \]  (46)

\[ \left( D^{LC} \wedge \bar{\gamma} \right)_{\mu}^{\nu} = g^{\mu\nu}(D^{LC}_{\rho}\bar{\gamma}_{\mu} - D^{LC}_{\mu}\bar{\gamma}_{\rho}) \]  (47)
Then, after a "straightforward" algebraic juggle, one finally obtains:

\[ Q_0^4 = \frac{\varepsilon_{\mu\nu}\varepsilon_{\rho\sigma}}{\sqrt{g}} g_{\nu\lambda} g_{\sigma\chi} (R^{LC})^\lambda_\mu \wedge (R^{LC})^\chi_\rho = E_\Sigma \]  
\( (48) \)

\[ Q_3^1 = 2 \frac{\varepsilon_{\mu\nu}\varepsilon_{\rho\sigma}}{\sqrt{g}} g_{\nu\lambda} g_{\sigma\chi} \left( -i_\Sigma(\omega) R^{LC} + \frac{1}{2} D^{LC} \wedge \bar{\gamma} \right)_\rho^\chi \]  
\( (49) \)

\[ Q_2^2 = \frac{\varepsilon_{\mu\nu}\varepsilon_{\rho\sigma}}{\sqrt{g}} g_{\nu\lambda} g_{\sigma\chi} \left[ \left( i_\Sigma(\omega) R^{LC} \right)^\lambda_\mu \wedge \left( i_\Sigma(\omega) R^{LC} \right)^\chi_\rho - 2 \left( i_\Sigma(\omega) R^{LC} \right)^\lambda_\mu \wedge \left( D^{LC} \wedge \bar{\gamma} \right)_\rho^\chi \right. 
\]  
\[ + \left( D^{LC} \wedge \bar{\gamma} \right)^\lambda_\mu \wedge \left( D^{LC} \wedge \bar{\gamma} \right)_\rho^\chi 
\]
\[ + \left( R^{LC} \right)^\lambda_\mu \wedge \left( i_\Sigma(\omega) i_\Sigma(\omega) R^{LC} - i_\Sigma(\omega) \left( D^{LC} \wedge \bar{\gamma} \right) - \frac{1}{2} \bar{\bar{\psi}} - D^{LC} \wedge \Omega \right)_\rho^\chi \]  
\( (50) \)

\[ Q_1^3 = \frac{\varepsilon_{\mu\nu}\varepsilon_{\rho\sigma}}{\sqrt{g}} g_{\nu\lambda} g_{\sigma\chi} \left( i_\Sigma(\omega) i_\Sigma(\omega) R^{LC} - i_\Sigma(\omega) D^{LC} \wedge \bar{\gamma} - \frac{1}{2} \bar{\bar{\psi}} - D^{LC} \wedge \Omega \right)^\lambda_\mu \]  
\[ \wedge \left( -i_\Sigma(\omega) R^{LC} + \frac{1}{2} D^{LC} \wedge \bar{\gamma} \right)_\rho^\chi \]  
\( (51) \)

\[ Q_0^4 = \frac{\varepsilon_{\mu\nu}\varepsilon_{\rho\sigma}}{4\sqrt{g}} g_{\nu\lambda} g_{\sigma\chi} \left( i_\Sigma(\omega) i_\Sigma(\omega) R^{LC} - i_\Sigma(\omega) D^{LC} \wedge \bar{\gamma} - \frac{1}{2} \bar{\bar{\psi}} - D^{LC} \wedge \Omega \right)^\lambda_\mu \]  
\[ \wedge \left( i_\Sigma(\omega) i_\Sigma(\omega) R^{LC} - i_\Sigma(\omega) D^{LC} \wedge \bar{\gamma} - \frac{1}{2} \bar{\bar{\psi}} - D^{LC} \wedge \Omega \right)_\rho^\chi \]  
\( (52) \)

Finally, the G’s are obtained by replacing \( \frac{\varepsilon_{\mu\nu}\varepsilon_{\rho\sigma}}{\sqrt{g}} g_{\nu\lambda} g_{\sigma\chi} \) in the Q’s by \( (\delta^\mu_\lambda \delta^\nu_\chi - \delta^\mu_\chi \delta^\nu_\lambda) \).

References

[AJ90] M.F. Atiyah and L. Jeffrey, "Topological Lagrangians and cohomology", Jour. of Geom. and Phys. Vol. 7, n. 1 (1990) 119.

[BT97] M. Bauer and F. Thuillier, "Representatives of the Thom class of a vector bundle", ENSLAPP-A-574/96 1996, to be published in Jour. of Geom. and Phys..
N. Berline, E. Getzler and M. Vergne, "Heat Kernels and Dirac Operators", Grundlehren des Mathematischen Wissenschasft 298, Springer-Verlag Berlin Heidelberg 1992.

L. Baulieu and I.M. Singer, "Topological Yang-Mills symmetry", Nucl. Phys. B Proc Supl 15B (1988) 12.

L. Baulieu and I.M. Singer, "Conformally Invariant Gauge Fixed Actions for 2-D Topological Gravity", Commun. Math. Phys. 135 (1991) 253.

H. Cartan, "Notion d’algèbre différentielle; application aux groupes de Lie et aux variétés où opère un groupe de Lie", Colloque de Topologie (Espaces Fibrés), Brussels 1950, CBRM, 15-56.

M. Dubois-Violette, private communication.

J. Kalkman, "BRST model for equivariant cohomology and representatives for the equivariant Thom class", Commun. Math. Phys. 153 (1993) 447.

S. Kobayashi and K. Nomizu, "Foundations of Differential Geometry", Vol 2, Interscience, London 1963.

R Stora, F. Thuillier and J.C. Wallet, "Algebraic structure of cohomological field theory models and equivariant cohomology", Lectures at the 1st Caribbean Spring School of Mathematics and Theoretical Physics, Saint François, Guadeloupe, May 30 - June 13 1993, Proceedings 1995 (preprint ENSLAPP-A-481/94).

E. Witten, "Topological quantum field theory", Commun. Math. Phys. 117 (1988) 353.

S. Wu, "Appearance of Universal Bundle Structure in four-dimensional Topological Gravity", Jour. of Geom. and Phys. 12 (1993) 205.