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A STRONG EXCISION THEOREM FOR GENERALISED TATE COHOMOLOGY

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We consider the analogue of the fixed point theorem of A. Borel in the context of Tate cohomology. We show that for general compact Lie groups G the Tate cohomology of a G-CW complex X with coefficients in a field of characteristic 0 is in general not isomorphic to the cohomology of the fixed point set, and thus the fixed point theorem does not apply. Instead, the following excision theorem is valid: if X' is the subcomplex of all G-cells of orbit type G/H where $\dim H > 0$, and V is a ring such that for every finite isotropy group H the order $|H|$ is invertible in V, then $\widehat{H}^*_G(X;V) \cong \widehat{H}^*_G(X';V)$. In the special cases $G = \mathbb{T}$, the circle group, and $G = \mathbb{U}$, the group of unit quaternions, a more elementary geometric proof, using a cellular model of $\widehat{H}^*_{\mathbb{U}}$ is given.

1. Introduction

The fixed point theorem of A. Borel states that for Abelian groups G and for suitable coefficients V the localised Borel equivariant cohomology $S^{-1}H^*_G(X;V)$ of a finite G-CW complex is isomorphic to the tensor product $H^*(F;V) \otimes S^{-1}H^*(BG;V)$ of the cohomology of the fixed point set F and the localised equivariant cohomology of a point [7, Proposition 1]. Thus, in this case, the cohomology of the fixed point set $H^*(F)$ is completely determined by the localised equivariant cohomology of X. For nonabelian groups this is far from true since any finite complex K can be the fixed point set of a compact finite-dimensional G-space X with trivial equivariant cohomology [7].

On infinite dimensional spaces it was shown by Goodwillie [5] that for $G = \mathbb{T}$, the circle group, the localised $\mathbb{T}$-equivariant Borel cohomology does not satisfy the fixed point theorem. Jones-Petrack [9], [10] and Cencelj [2] constructed a completed localised $\mathbb{T}$-equivariant cohomology which coincides with the classical Borel one on finite dimensional spaces, and for which the fixed point theorem holds also for infinite dimensional spaces and suitable coefficient rings. This cohomology essentially coincides with the special case of $G = \mathbb{T}$ of the generalised Tate cohomology $\widehat{H}^*_{\mathbb{T}}$ of Greenlees and May [6] (with

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underlying Borel equivariant cohomology), which is defined generally, for any compact Lie group G. In this note we study the fixed point theorem for this cohomology, which we denote by $\widehat{H}^*_G$. We show that, as in the case of localised Borel equivariant cohomology, the fixed point theorem does not hold for infinite groups G, different from $\mathbb{T}$. Instead, we prove the following excision theorem:

THEOREM 1. *Let G be a compact Lie group, X a G-CW complex, and X' the subcomplex containing all cells of type G/H, where $\dim H > 0$. If V is a ring such that for every finite isotropy group H the order $|H|$ is invertible in V, then $\widehat{H}^*_G(X;V) \cong \widehat{H}^*_G(X',V)$.*

The proof depends on the fact that the cohomology $\widehat{H}^*_G(\mathcal{O};V)$ of any orbit $\mathcal{O} = G/H$, where H is finite and $|H|$ is invertible in V, is trivial. We first prove this for the circle group $G = \mathbb{T}$, and for the group $G = \mathbb{U}$ of unit quaternions (Proposition 1). These two cases have an additional geometric side since, for a smooth manifold X, the cohomology $\widehat{H}^*G(X;\mathbb{R})$ is expressible in terms of invariant differential forms on X. In addition, Tate cohomology $\widehat{H}^*_G(X)$ of a G-CW complex X can be, in these two cases, computed from a nonequivariant cellular decomposition of X by [**6**, 10.3, 14.9]. This follows from two properties of these two groups. First, by [**6**, 14.1] and [**3**, Theorem 1], every G-CW complex X has a G-homotopy equivalent CW complex Y with an action of G such that the action map $\mu : G\times Y \to Y$ is cellular, which implies that $GY^n \subset Y^{n+d}$ for all n, where $d = 1$ in the case of $\mathbb{T}$ and $d = 3$ in the case of $\mathbb{U}$. It is not known which compact Lie groups have this property. Apart from finite groups and the groups $\mathbb{T}$ and $\mathbb{U}$ it has been shown for all toral groups [**4**]. Second, in these two cases the classifying space EG has a CW decomposition with cells only in dimensions apart by d, and therefore any G-CW complex is calculable in the sense of [**6**, 10.1]. In Section 2 we use nonequivariant cellular decompositions to compute the cohomology $\widehat{H}^*_G(\mathcal{O})$ of the orbits $\mathcal{O} = G/H$, where G is either $\mathbb{T}$ or $\mathbb{U}$. In the case $G = \mathbb{T}$ this leads to a new proof of the fixed point theorem of [**2**], and in the case $G = \mathbb{U}$ it follows that the fixed point theorem is not valid, and the excision theorem 1 follows.

In Section 3 we prove that for any compact Lie group G and any finite subgroup H such that the order $|H|$ is invertible in the coefficient ring V the Tate cohomology $\widehat{H}^*_G(G/H;V) = 0$. The proof follows from general properties of Tate cohomology. In Section 4, the proof of the excision theorem is given.

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2. TATE COHOMOLOGY OF ORBITS OF $\mathbb{T}$ AND $\mathbb{U}$

Equivariant cohomology for the circle group $\mathbb{T}$ and the group of unit quaternions $\mathbb{U}$ has several geometric properties which justify a special treatment. Throughout this section, G will denote one of the groups $\mathbb{T}$ and $\mathbb{U}$.

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It is known [**6**] that, up to minor differences, $\widehat{H}_{\mathbb{T}}(X)$ coincides with localised cyclic cohomology of Jones [**8**], [**9**]. If X is a smooth $\mathbb{T}$-manifold, then this cohomology with coefficients in a field of characteristic 0 (for example $\mathbb{C}$) is expressible in terms of invariant differential forms on X. More precisely, $\widehat{H}^*_{\mathbb{T}}(X;\mathbb{C})$ is the cohomology of the complex $\Omega^*_{\mathbb{T}}(X)[[u,u^{-1}]]$ of invariant differential forms on X and u is of degree 2 with the differential $d_{\mathbb{T}} = d + uj$, where d is the exterior derivative and $j : \Omega^n_{\mathbb{T}} \to \Omega^{n+1}_{\mathbb{T}}$ is integration of differential forms along orbits of the action [**9**]. It was shown in [**2**] that this cohomology satisfies the fixed point theorem. Similarly, $\widehat{H}^*_{\mathbb{U}}(X;\mathbb{C})$ where X is a smooth $\mathbb{U}$-manifold coincides with the cohomology of the complex $\Omega^*_{\mathbb{U}}(X)[[u,u^{-1}]]$ of $\mathbb{U}$-invariant forms on X, where u is of degree 4, the differential is $d_{\mathbb{U}} = d + uj$, and $j : \Omega^n_{\mathbb{U}} \to \Omega^{n+3}_{\mathbb{U}}$ is again integration along orbits of the action.

In both cases, $G = \mathbb{T}$ and $G = \mathbb{U}$, Tate cohomology $\widehat{H}^*_G(X)$ of a G-CW complex X has a description in terms of a nonequivariant cellular decomposition of X. Let $C(G)$ be the standard cellular chain complex of $G \cong S^r$ arising from the CW decomposition with one 0-cell and one r-cell, where $r = 1$ in case $G = \mathbb{T}$ and $r = 3$ in case $G = \mathbb{U}$, and let $z \in C_r(G)$ correspond to the r-cell. The product $\pi : G \times G \to G$ is a cellular map which, on the chain level, maps $z \otimes z$ to 0.

For every G-CW complex X there exists a G-homotopy equivalent CW complex Y such that the action $\mu : Y \times G \to Y$ is a cellular map [**6**, Lemma 14.1], [**3**, Theorem 1]. As in [**6**], let $(C(Y), d)$ be the cellular chain complex of Y and let $J : C_j(Y) \to C_{j+r}(Y)$ be given by $J(c) = \mu_*(z \otimes c)$. The operator J, which corresponds to the integration operator j in the case of differential forms on X, has the properties: $dJ = -Jd$ and $J^2 = 0$ and so gives rise to the bicomplex $\mathbb{Z}[u,u^{-1}] \otimes C(Y)$, where the powers u^{-n} represent generators of the standard cellular complex of BG (that is, u is of degree $-(r+1)$) with differential

$$d(w \otimes c) = uw \otimes J(c) + w \otimes d(c).$$

By [**6**, Theorem14.9], Tate cohomology $\widehat{H}^*_G(X;V)$ coincides with the cohomology

$$H^*\Big(\mathrm{Hom}\big(\mathbb{Z}[u,u^{-1}] \otimes C(Y); V\big)\Big)$$

for any coefficient ring V.

Using this description we can compute the Tate cohomology of the orbits $\mathcal{O} = G/H$, where $H < G$ is a closed subgroup.

All closed subgroups of $\mathbb{T}$, different from $\mathbb{T}$, are finite cyclic groups. The isomorphism classes of closed subgroups of $\mathbb{U}$ consist of two 1-dimensional subgroups: the maximal torus $\mathbb{T}$ and its normaliser, and the following 0-dimensional subgroups: the cyclic groups $\mathbb{Z}/n$, the quaternionic groups $\langle x, y \mid x^n = y^2, y^{-1}xy = x^{-1}\rangle$, the special linear group $SL_2(\mathbb{F}_3)$ (a lift of the tetrahedral subgroup of $SO(3)$), the special linear group $SL_2(\mathbb{F}_5)$ (a lift of the icosahedral subgroup of $SO(3)$), and the lift of the octahedral subgroup of $SO(3)$ (an extension of the symmetric group S_4) [**12**, p. 155], [**11**, p. 404]. Every isomorphism class contains precisely one conjugacy class (this is proved for example in [**3**]).

Proposition 1. *For every finite closed subgroup $H < G$, where G is either $\mathbb{T}$ or $\mathbb{U}$, and for every coefficient ring V such that $m = |H|$ is invertible in V,*

$$\widehat{H}^*_G(\mathcal{O}; V) = 0.$$

Proof: In order to compute $\widehat{H}^*_{\mathbb{U}}(\mathcal{O}; V)$, we compute the cohomology of the bicomplex $\mathbb{Z}[u, u^{-1}] \otimes C(\mathcal{O})$.

Let us first consider the more complicated case $G = \mathbb{U}$. If $H < \mathbb{U}$ is finite, the orbit $\mathcal{O} = \mathbb{U}/H$ has cells in dimension 0, 1, 2, and 3. A finite part of the bicomplex $\mathbb{Z}[u, u^{-1}] \otimes C(\mathcal{O})$ is on figure 1, where the vertical arrows are the differential d of $C(\mathcal{O})$ and the horizontal arrows are the operator $\widetilde{J} = u \otimes J(\_)$.

$$\begin{array}{ccccccc}
 & & & & \downarrow & & \downarrow \\
 & & 0 & \longleftarrow & 1 \otimes C_3(\mathcal{O}) & \longleftarrow & u^{-1} \otimes C_0(\mathcal{O}) \\
 & & & & \downarrow & & \\
 & & 0 & \longleftarrow & 1 \otimes C_2(\mathcal{O}) & \longleftarrow & 0 \\
 & & & & \downarrow & & \\
 & & 0 & \longleftarrow & 1 \otimes C_1(\mathcal{O}) & \longleftarrow & 0 \\
 & & \downarrow & & \downarrow & & \\
0 & \longleftarrow & u \otimes C_3(\mathcal{O}) & \longleftarrow & 1 \otimes C_0(\mathcal{O}) & \longleftarrow & 0 \\
 & & \downarrow & & & & \\
0 & \longleftarrow & u \otimes C_2(\mathcal{O}) & \longleftarrow & 0 & & \\
 & & \downarrow & & & &
\end{array}$$

Figure 1: A part of the bicomplex $\mathbb{Z}[u, u^{-1}] \otimes C(\mathbb{U}/H)$, H finite. The vertical arrows are d and the horizontal arrows are $\widetilde{J} = u \otimes J(\_)$.

It follows that on cohomology

$$\widehat{H}^0_{\mathbb{U}}(\mathcal{O}; V) \cong H^0(\mathcal{O}; V)/\operatorname{Im} \widetilde{J}^*, \quad \widehat{H}^3_{\mathbb{U}}(\mathcal{O}; V) \cong \ker \widetilde{J}^* < H^3(\mathcal{O}; V). \tag{1}$$

Clearly $J = 0$ on elements of dimension $1, 2$, and 3. Since the projection $p : \mathbb{U} \to \mathcal{O} = \mathbb{U}/H$ is a m-fold covering projection, where $m = |H|$, the operator J maps an element

$a \in C_0(\mathcal{O})$ representing the generator of $H_0(\mathcal{O})$ to

$$J(a) = \mu_*(z \otimes a) = p_*(z) = mb,$$

where $b \in C_3(\mathcal{O})$ represents the fundamental class $[\mathcal{O}] \in H_3(\mathcal{O})$. So $J^* : C^3(\mathcal{O}) \to C^0(\mathcal{O})$ induces multiplication by m on cohomology, and is an isomorphism since m is invertible in V. By (1),

$$\widehat{H}^0_{\mathbb{U}}(\mathcal{O}; V) = \widehat{H}^3_{\mathbb{U}}(\mathcal{O}; V) = 0.$$

In dimensions 1 and 2 we have

$$\widehat{H}^1_{\mathbb{U}}(\mathcal{O}; V) = H^1(\mathcal{O}; V), \quad \widehat{H}^2_{\mathbb{U}}(\mathcal{O}; V) = H^2(\mathcal{O}; V).$$

Since $\mathbb{U} \cong S^3$ is the universal cover of $\mathcal{O}$, $H_1(\mathcal{O}; \mathbb{Z}) = Ab(H)$ is a torsion group, and the order, which divides m, is invertible in V so, by the universal coefficients theorem $H_1(\mathcal{O}; V) = 0$ and $H^1(\mathcal{O}; V) = 0$. By Poincaré duality also $H^2(\mathcal{O}; V) = 0$.

If $G = \mathbb{T}$, then $\mathcal{O} \cong S^1$ has a cell in dimensions 0 and 1. The bicomplex $\mathbb{Z}[u, u^{-1}] \otimes C(\mathcal{O})$ is on figure 2. By the same arguments as above, $J^* : C^1(\mathcal{O}) \to C^0(\mathcal{O})$ is an isomorphism, and

$$\widehat{H}^0(\mathcal{O}; V) = \widehat{H}^1(\mathcal{O}; V) = 0.$$

$$\begin{array}{ccccccccc}
 & & & & & & \downarrow & & \downarrow \\
 & & 0 & \leftarrow & 1\otimes C_1(\mathcal{O}) & \leftarrow & u^{-1}\otimes C_0(\mathcal{O}) & \leftarrow & 0 \\
 & & & & \downarrow & & \downarrow & & \\
0 & \leftarrow & u\otimes C_1(\mathcal{O}) & \leftarrow & 1\otimes C_0(\mathcal{O}) & \leftarrow & 0 & & \\
 & & \downarrow & & \downarrow & & & &
\end{array}$$

Figure 2: A part of the bicomplex $\mathbb{Z}[u, u^{-1}] \otimes C(\mathbb{T}/H)$, $H < \mathbb{T}$.

The vertical arrows are d and the horizontal arrows are $\widetilde{J} = u \otimes J(\_)$. ∎

Proposition 2. *For every closed subgroup $H < \mathbb{U}$ where $\dim H > 0$ and any coefficient ring V*

$$\widehat{H}^*_{\mathbb{U}}(\mathcal{O}; \mathbb{Z}) \neq 0.$$

Proof: Since closed subgroups of $\mathbb{U}$ are of dimension either 0 or 1, H is 1-dimensional, and the orbit $\mathcal{O}$ has cells in dimensions 0, 1, and 2. A finite part of the bicomplex $\mathbb{Z}[u, u^{-1}] \otimes C(\mathcal{O})$ in on figure 3.

Clearly $J = 0$, so $\widehat{H}^*_{\mathbb{U}}(\mathcal{O}; k) \cong H^*(X; \mathbb{Z})[u, u^{-1}]$ is nonzero in dimensions 0 and 2. ∎

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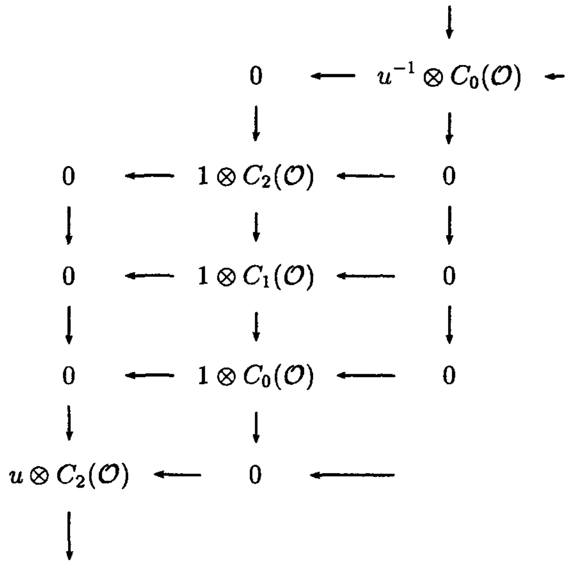

Figure 3: A part of the bicomplex $\mathbb{Z}[u,u^{-1}]\otimes C(\mathbb{U}/H)$, $\dim H>0$. The vertical arrows are d and the horizontal arrows are $\widetilde{J}=u\otimes J(\_)$.

It follows from proposition 2 that the fixed point theorem for $G=\mathbb{U}$ is not valid. An orbit $\mathcal{O}=\mathbb{U}/H$ where $\dim H=1$ is a $\mathbb{U}$-CW complex with nontrivial Tate cohomology at least in dimension 0 for any coefficient ring. The fixed point set F of the action is empty, though, so clearly $\widehat{H}^*_{\mathbb{U}}(\mathcal{O};V)\neq\widehat{H}^*_{\mathbb{U}}(F;V)$.

3. Tate cohomology of orbits of general compact Lie groups

It remains to prove the theorem for general compact Lie groups. In order to do this, we shall show that proposition 1 is in fact valid for any compact Lie group G, that is, an orbit of type G/H where H is finite has trivial Tate cohomology with coefficients in any ring V such that the order $|H|$ is invertible in V.

For a general compact Lie group G, the ordinary reduced G-equivariant Tate cohomology $\widehat{H}^*_G(X;V)$ of a G space X with coefficients in a $\pi_0(G)$-module V is obtained by splicing the homology and cohomology of the Borel construction $EG\times_G X$. Formally it is defined in [**6**] in the following way. Let M be a Mackey functor, that is, an additive contravariant functor from the full subcategory of G-spectra containing as objects suspension spectra of orbits G/H_+, such that $M(G/e)=V$, and let HM be the Eilenberg-MacLane G-spectrum of M, that is, the G-spectrum, unique up to homotopy, such that for each

$H < G$,

$$\pi_n(HM^H) = [S^n, HM]_H = [G/H_+ \wedge S^n, HM]_G = 0, \quad n > 0,$$
$$\pi_0(HM^H) = [S^0, HM]_H = [G/H_+ \wedge S^0, HM]_G = M(G/H).$$

Let EG be a universal space for G, that is, a contractible space with a free action of G, and $\widetilde{EG}$ the unreduced suspension of EG. Then

$$\widehat{H}^n_G(X;V) = t(HM)^n(X) = \left[X \wedge S^{-n}, t(HM)\right]_G,$$

where, for a G-spectrum k_G,

$$t(k_G) = F(EG_+, k_G) \wedge \widetilde{EG},$$

and $F(X, k_G)$ is the G-spectrum of pointed maps with the conjugate action of G.

Proposition 3. *For any compact Lie group G and any finite closed subgroup $H < G$, such that $m = |H|$ is invertible in V, the Tate cohomology $\widehat{H}^*_G(G/H_+;V)$ is trivial.*

Proof: Since $[G/H_+, X]_G = [S^0, X]_H$, it follows directly from the definition of Tate cohomology that

$$\widehat{H}^n_G(G/H_+;V) = \widehat{H}^n_H(S^0;V). \tag{2}$$

Since EG is a model for EH, the G-spectrum k_G, viewed as an H-spectrum is equivalent to k_H [**6**, Proposition 3.7]. For every orbit G/H, the Borel construction $(G/H_+ \times_G EG)$ is, over H, equivalent to

$$(S^0 \times_H EH) = (S^0 \times BH),$$

so the reduced Tate cohomology is

$$\widehat{H}^*_G(G/H_+;V) = \widehat{H}^*_H(S^0;V). \tag{3}$$

If H is finite, this is equal to ordinary unreduced Tate cohomology $\widehat{H}^*(H,V)$ of the finite group H. It is a classical result that this is 0 if the order of H is invertible in V. This can be proved using transfer in the following way. Tate cohomology of finite groups is obtained by splicing homology and cohomology ([**1**, p. 134]). If $i : \{e\} \to H$ is inclusion of the trivial subgroup and tr is the transfer, then the composition $(tr \circ i)$ induces multiplication by $|H|$ on homology and on cohomology. Since $|H|$ is invertible in V, these are both isomorphisms, which factorise through $H_*(\{e\}, V) = 0$ and $H^*(\{e\}, V) = 0$ respectively. It follows that $\widehat{H}^*(H,V) = 0$ for all $n \neq -1, 0$. In dimensions $n = -1, 0$ it follows from the exact sequence

$$0 \longrightarrow \widehat{H}^{-1}(H,V) \longrightarrow H_0(H,V) \xrightarrow{\overline{N}} H^0(H,V) \longrightarrow \widehat{H}^0(H,V) \longrightarrow 0$$

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that $\widehat{H}^0(H,V) = \widehat{H}^{-1}(H,V) = 0$ since the norm map

$$\overline{N} : H_0(H,V) \cong V_H \to H^0(H,V) \cong V^H$$

is clearly an isomorphism in this case [**1**]. ∎

If $\dim H = d > 0$, then the Tate cohomology of an orbit G/H is expressed in terms of ordinary homology and cohomology of the classifying space BH in the following way:

$$\widehat{H}_G^*(G/H_+;V) \cong \widehat{H}_H^*(S^0;V) \cong \begin{cases} H^n(BH;V) & \text{if } 0 \leqslant n \\ 0 & \text{if } -d \leqslant n < 0 \\ H_n(BH;V) & \text{if } n \leqslant -d-1 \end{cases},$$

which is nonzero for many choices of V.

4. Proof of the excision theorem

The proof of the excision theorem now follows directly from the following lemma which is proved by standard homological arguments.

Lemma 1. *Let G be a compact Lie group, let X be a G-CW complex and X' a subcomplex. Assume that X is obtained from X' by attaching G-cells such that for any subgroup $H < G$ appearing as isotropy type of an attached cell, $\widehat{H}_G^*(G/H_i;V) = 0$. Then $\widehat{H}_G^*(X;V) = \widehat{H}_G^*(X';V)$.*

Proof: The proof goes by induction on the dimension of the G-cells. Assume that $X'' < X$ is obtained by attaching all cells w_i^q of types G/H of X and of dimension $q \leqslant (n-1)$ to X'. Let $\coprod w_\alpha^n$ be the disjoint union of all cells of dimension n in X which are not in X'. In the exact sequence of the couple $(X'' \cup \coprod w_\alpha^n, X'')$

$$\cdots \to \widehat{H}_G^q\left(X'' \cup \coprod w_\alpha^n, X''\right) \to \widehat{H}_G^q\left(X'' \cup \coprod w_\alpha^n\right) \to \widehat{H}_G^q(X'') \to \cdots$$

the left term is

$$\widehat{H}_G^q\left(X'' \cup \coprod w_\alpha^n, X''\right) \cong \oplus_\alpha \widehat{H}_G^q(w_\alpha^n, \partial w_\alpha^n).$$

For each α,

$$\widehat{H}_G^q(w_\alpha^n, \partial w_\alpha^n) \cong (\mathcal{O} \times D^m, \mathcal{O} \times S^{m-1}),$$

where $\mathcal{O}$ is the orbit G/H. Since $\widehat{H}_G^*(\mathcal{O}) = 0$, it follows by induction on m that also $\widehat{H}_G^*(\mathcal{O} \times D^m, \mathcal{O} \times S^{m-1}) = 0$, and therefore $\widehat{H}_G^*\left(X'' \cup \coprod w_\alpha^n, X''\right)$ in the exact sequence is trivial so $\widehat{H}_G^*(X'' \cup w_n) \cong \widehat{H}_G^*(X'')$. ∎

In the special case $G = \mathbb{T}$, all proper close subgroups are finite and the excision theorem for $G = \mathbb{T}$ is reduced to the following reformulation of the fixed point theorem of [**2**].

Corollary 1. *For any $\mathbb{T}$-CW complex X and for any coefficient ring V such that the order of each isotropy group H of X is invertible in V*

$$\widehat{H}^*_{\mathbb{T}}(X;V) \cong \widehat{H}^*_{\mathbb{T}}(F;V) \cong H^*(F;V)\big[[u,u^{-1}]\big],$$

where $F \subset X$ is the set of fixed points of the action, and u is of degree 2.

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