A THEORY OF CHARACTERISTIC CURRENTS
ASSOCIATED WITH A SINGULAR CONNECTION

RESEbEE HARVEY AND H. BLAINE LAWSON, JR.

ABSTRACT. This note announces a general construction of characteristic currents for
singular connections on a vector bundle. It develops, in particular, a Chern-Weil-
Simons theory for smooth bundle maps \( \alpha : E \to F \) which, for smooth connections on
\( E \) and \( F \), establishes formulas of the type

\[
\phi = \text{Res}_\phi \Sigma_\alpha + dT.
\]

Here \( \phi \) is a standard characteristic form, \( \text{Res}_\phi \) is an associated smooth “residue” form
computed canonically in terms of curvature, \( \Sigma_\alpha \) is a rectifiable current depending
only on the singular structure of \( \alpha \), and \( T \) is a canonical, functorial transgression
form with coefficients in \( L^1_{\text{loc}} \). The theory encompasses such classical topics as:
Poincaré-Lelong Theory, Bott-Chern Theory, Chern-Weil Theory, and formulas of Hopf. Applications include: a new proof of the Riemann-Roch Theorem for vector
bundles over algebraic curves, a \( C^\infty \)-generalization of the Poincaré-Lelong Formula,
universal formulas for the Thom class as an equivariant characteristic form (i.e.,
canonical formulas for a de Rham representative of the Thom class of a bundle with
connection), and a Differentiable Riemann-Roch-Grothendieck Theorem at the level
of forms and currents. A variety of formulas relating geometry and characteristic
classes are deduced as direct consequences of the theory.

1. Introduction

Our purpose is to announce a generalized Chern-Weil theory for singular connections on a vector bundle, particularly those which arise from bundle maps. Specifically, if \( E \) and \( F \) are smooth vector bundles with connection over a manifold \( X \), the theory associates to each homomorphism \( \alpha : E \to F \) a family of \( d \)-closed
currents on \( X \) defined canonically in terms of the curvature of the bundles and the singularities of the map \( \alpha \).

One can focus attention either on \( E \) or on \( F \) (and retrieve, when \( \alpha \equiv 0 \), the
standard theory for \( E \) or \( F \)). Suppose the focus is on \( F \), and fix a characteristic

\begin{itemize}
\item 1991 Mathematics Subject Classification. Primary 53C07, 49Q15; Secondary 58H99, 57R20.
\item Research of both authors was supported by the National Science Foundation
\item Received by the editors October 6, 1992 and, in revised form, August 20, 1993
\end{itemize}

\( \copyright 1994 \) American Mathematical Society
\texttt{0273-0979/94 81.00 + $.25 per page}
polynomial \( \phi \), i.e., an Ad-invariant polynomial on the Lie algebra of the structure group of \( F \). The new theory associates to \( \phi \) a \( d \)-closed current \( \phi(\Omega_{F,\alpha}) \) which is defined in terms of curvature and the singular structure of \( \alpha \) and which represents the characteristic class \( \phi(F) \). Moreover, the theory constructs a canonical and functorial transgression current \( T = T(\phi, \alpha) \) with the property that
\[
\phi(\Omega_F) - \phi(\Omega_{F,\alpha}) = dT.
\]

When \( \text{rank}(E) = \text{rank}(F) \), this often yields an equation of the form
\[
\phi(\Omega_F) - \phi(\Omega_E) = \text{Res}_\phi[\Sigma] + dT
\]
where \([\Sigma]\) is the current given by integration over the singular set \( \Sigma \) \( \overset{\text{def}}{=} \{ x \in X : \alpha_x \text{ is not an isomorphism} \} \) and where \( \text{Res}_\phi \) is a smooth “residue” form which is expressed canonically in terms of the curvatures \( \Omega_E \) and \( \Omega_F \) of \( E \) and \( F \). One can think of \( S_\phi = \text{Res}_\phi[\Sigma] \) as the characteristic current associated to \( \alpha : E \to F \) which represents the class \( \phi(F) - \phi(E) \in H^*_\text{de Rham}(X) \).

When \( \text{rank}(E) > \text{rank}(F) \), there are analogous formulas:
\[
\phi(\Omega_E) - \phi(\Omega_0) = \text{Res}_\phi[\Sigma] + dT
\]
where \( \phi(\Omega_0) \) is a closed differential form with \( L^1_{\text{loc}}(X) \)-coefficients whose cohomology class is more subtly determined by the global geometry.

2. An example: Complex line bundles

Suppose that \( E \) and \( F \) are complex line bundles over an oriented manifold \( X \) and that \( \alpha : E \to F \) is a smooth bundle map. If \( \alpha \) vanishes nondegenerately, we define its divisor to be the current \( \text{Div}(\alpha) = [\Sigma] \) associated to the oriented codimension-2 submanifold \( \Sigma = \{ x \in X : \alpha_x = 0 \} \). Set
\[
f = \frac{1}{2\pi} \Omega_F \quad \text{and} \quad e = \frac{1}{2\pi} \Omega_E
\]
where \( \Omega_E \) and \( \Omega_F \) are the curvature 2-forms of the connections. Then it is shown that there exists a 1-form \( \sigma \) on \( X \) with \( L^1_{\text{loc}}(X) \)-coefficients such that
\[
f - e = \text{Div}(\alpha) + \frac{i}{2\pi} d\sigma,
\]
where \( \sigma \) is defined by \( D\alpha = \sigma \alpha \). Passing to cohomology, we capture the first Chern class \( c_1(F) - c_1(E) = [f] - [e] = [\text{Div}(\alpha)] \in H^2_\text{de Rham}(X) \). Note that when \( E \) is trivial, equation (1) represents a \( C^\infty \) enhancement of the classical Poincaré-Lelong Formula for sections of the bundle \( F \).

More precisely, formula (1) is shown to hold for any bundle map \( \alpha \) which is \emph{atomic}, that is, for which
\[
\frac{da}{a} \in L^1_{\text{loc}}(X),
\]
where \( a \) is the complex-valued function which represents \( \alpha \) in the given local frames. This condition is independent of the choice of frames, as is the closed current \( \text{Div}(\alpha) = d \left( \frac{1}{2\pi i} \frac{da}{a} \right) \) (cf. [HS]). Note that locally \( \sigma = \frac{da}{a} + \omega_F - \omega_E \). The following general result is formula (1) when \( \phi(u) = u \).
Theorem A. Fix a polynomial \( \phi(u) \in \mathbb{C}[u] \) in one indeterminate. Then for any atomic bundle map \( \alpha : E \to F \) as above, there exists a differential form \( T \) with \( L^1_{\text{loc}} \)-coefficients on \( X \) such that

\[
\phi(f) - \phi(e) = \left\{ \frac{\phi(f) - \phi(e)}{f - e} \right\} \text{Div}(\alpha) + dT
\]

where \( \frac{\phi(f) - \phi(e)}{f - e} \) is the obvious polynomial in \( e \) and \( f \). In fact, the \( L^1_{\text{loc}}(X) \)-form \( T \) is given explicitly by

\[
T = \frac{1}{2\pi} \left\{ \frac{\phi(f) - \phi(e)}{f - e} \right\} \sigma.
\]

Combining this result with the kernel-calculus of Harvey and Polking [HP] yields a new proof of the Riemann-Roch Theorem for vector bundles over algebraic curves.

3. The general procedure; approximation modes

Let \( E \) and \( F \) be smooth vector bundles with connections \( D_E \) and \( D_F \) over a manifold \( X \) where, for simplicity in the following discussion, we assume \( \text{rank}(E) \leq \text{rank}(F) \). Now for bundle maps

\[
\alpha : E \to F \quad \text{and} \quad \beta : F \to E
\]

these connections can be transplanted via the formulas

\[
\overleftarrow{D}^{\alpha,\beta} = \beta \circ D_F \circ \alpha + (1 - \beta \alpha) \circ D_E \quad \text{and} \quad \overrightarrow{D}^{\alpha,\beta} = \alpha \circ D_E \circ \beta + D_F \circ (1 - \alpha \beta)
\]

to define induced connections on \( E \) and \( F \) respectively. When \( E \) and \( F \) are isomorphic and \( \beta = \alpha^{-1} \), one recovers the standard gauge transformations. If \( \alpha \) is injective, one can introduce metrics on \( E \) and \( F \) and define

\[
\beta = (\alpha^* \alpha)^{-1} \alpha^*.
\]

yielding a pull back connection \( \overleftarrow{D} \) and a push forward connection \( \overrightarrow{D} \). In general this procedure breaks down on the singular set \( \Sigma \equiv \{ x : \alpha_x \text{ is not injective} \} \), since \( \beta \) becomes singular on \( \Sigma \). To remedy this, we choose an approximation mode by fixing a \( C^{\infty} \)-function \( \chi : [0, \infty] \to [0, 1] \) with \( \chi' \geq 0, \chi(0) = 0, \text{and} \chi(\infty) = 1 \). We then define a smooth approximation \( \beta_s \) to \( \beta \) by

\[
\beta_s = \chi \left( \frac{\alpha^* \alpha}{s} \right) \beta \quad \text{for} \ s > 0.
\]

Plugging \( \beta_s \) into the formulas above gives a family of smooth connections \( \overleftarrow{D}_s \) on \( F \) (and \( \overrightarrow{D}_s \) on \( E \)). As \( s \to 0, \beta_s \to \beta \) uniformly on compacta in \( X - \Sigma \). If \( \chi(t) \equiv 1 \) for \( t \geq 1 \), then \( \beta_s = \beta \) outside the neighborhood \( \{ x \in X : ||\alpha_x||^2 < s \} \) of \( \Sigma \). Such a choice of \( \chi \) is called a compactly supported approximation mode. Another important case is the algebraic approximation mode where \( \chi(t) = t/(1+t) \). Here the family of connections \( \overleftarrow{D}_s \) is directly related to the Grassmann graph construction of R. MacPherson. When working in this mode with the tautological bundle map \( \alpha : \pi^*E \to \pi^*F \) over the total space of \( \pi : \text{Hom}(E, F) \to X \), the family \( \overleftarrow{D}_s \) extends smoothly to a fibrewise compactification of \( \text{Hom}(E, F) \). This has strong consequences for characteristic forms in the curvature of \( \overleftarrow{D}_s \).

Let \( \Omega_s \) denote the curvature of \( \overleftarrow{D}_s \), and fix an Ad-invariant polynomial \( \phi \) on the Lie algebra of the structure group of \( F \).
Definition A. Suppose that the limit
\[
\phi(\overrightarrow{D}) \overset{\text{def}}{=} \lim_{s \to 0} \phi(\overrightarrow{\Omega}_s)
\]
exists as a current on \(X\). Then \(\phi(\overrightarrow{D})\) is called the \(\phi\)-characteristic current associated to the singular push forward connection \(\overrightarrow{D}\) on \(F\). An analogous definition holds for the singular pull back connection \(\overleftarrow{D}\) on \(E\).

Note that \(\phi(\overrightarrow{D})\) is automatically \(d\)-closed and represents the \(\phi\)-characteristic class of \(F\). Over the subset \(X - \Sigma\), \(\overrightarrow{D}\) is a smooth connection, and \(\phi(\overrightarrow{D})\) is a smooth differential form which we denote by \(\phi(\overrightarrow{\Omega}_0)\). Note that when \(\text{rank}(E) = \text{rank}(F)\), \(\overrightarrow{D}\) is gauge equivalent via \(\alpha\) to \(D_E\) over \(X - \Sigma\), and therefore \(\phi(\overrightarrow{\Omega}_0) = \phi(\Omega_E)\) extends smoothly across the singular set \(\Sigma\). When \(\text{rank}(E) < \text{rank}(F)\), [HL1] establishes conditions on \(\alpha\) which guarantee that \(\phi(\overrightarrow{\Omega}_0)\) extends across \(\Sigma\) as a \(d\)-closed \(L^1_{\text{loc}}\)-form. This gives a decomposition

\[
\phi(\overrightarrow{D}) = \phi(\overrightarrow{\Omega}_0) + S\phi
\]

where \(\phi(\overrightarrow{\Omega}_0)\) denotes the \(L^1_{\text{loc}}(X)\)-extension and where \(S\phi\) is a current on \(X\) with the property that
\[
d S\phi = 0 \quad \text{and} \quad \text{supp}(S\phi) \subseteq \Sigma.
\]

Each term in (3) represents a de Rham cohomology class on \(X\) which can be nonzero even when \(E\) and \(F\) are trivial bundles.

The detailed structure of \(S\phi\) and its independence of approximation mode is established by considering a family of transgression forms \(T_s\) with
\[
d T_s = \phi(\Omega_F) - \phi(\overrightarrow{\Omega}_s)
\]

and finding conditions on \(\alpha\) so that \(T \overset{\text{def}}{=} \lim_{s \to 0} T_s\) exists in \(L^1_{\text{loc}}(X)\). The transgression \(T\) satisfies
\[
d T = \phi(\Omega_F) - \phi(\overrightarrow{\Omega}_0) - S\phi
\]

and is functorial under appropriately transverse maps between manifolds. In many cases \(S\phi\) can be written as
\[
S\phi = \text{Res}_\phi[\Sigma]
\]

where \(\text{Res}_\phi\) is a smooth form on \(X\), expressed as a universal Ad-invariant polynomial in \(\Omega_E\) and \(\Omega_F\). In particular \(\text{Res}_\phi\) is completely determined by computing its associated cohomology class in the universal setting.

Combining this gives a Chern-Weil Theorem for bundle maps:

\[
\phi(\Omega_F) - \phi(\overrightarrow{\Omega}_0) = \text{Res}_\phi[\Sigma] + dT
\]

where \([\Sigma]\) is a current canonically determined by the singular structure of \(\alpha\). Special cases are discussed in the following sections.
4. Universal Thom classes

When \( E \) is the trivial line bundle, \( \alpha \) becomes a cross-section of \( F \).

**Definition B.** The cross-section \( \alpha \) is said to be atomic if whenever \( \alpha \) is written locally as \( \alpha = \sum a_i e_j \) in terms of a local frame field \( e \), the \( \mathbb{R}^m \)-valued function \( a = (a_1, \ldots, a_m) \) satisfies

\[
\frac{da_I}{|a|^{|I|}} \in L^1_{\text{loc}}(X) \quad \text{for all } |I| < m.
\]

Elementary criteria for atomicity are given in [HS]. Roughly speaking, any smooth section which vanishes “algebraically” on a set of the appropriate “Minkowski codimension” is atomic. For example, any real analytic section with zeros of codimension \( \geq m \) is atomic.

It is proved in [HS] that the vanishing of an atomic section \( \alpha \) determines a unique, \( d \)-closed current \( \text{Div}(\alpha) \) of real codimension-\( m \), called the divisor of \( \alpha \). Locally, the divisor is defined by

\[
\text{Div}(\alpha) = \frac{d}{d\theta(\alpha^* \theta)}
\]

where \( \theta \) is the normalized solid angle kernel on \( \mathbb{R}^m \). This current \( \text{Div}(\alpha) \) is integrally flat, and in particular, when its mass is finite, it is a rectifiable cycle in the sense of Federer [F].

Suppose that \( F \) is either complex, or real and oriented, and that \( \phi \) is the top Chern polynomial \( \tilde{\det}(A) = \det(\frac{1}{2\pi} A) \) or the Euler polynomial \( \tilde{\text{Pf}}(A) = \text{Pfaff}(-\frac{1}{2\pi} A) \) respectively. (If \( \dim_{\mathbb{R}} F \) is odd, then \( \phi \equiv 0 \).) When \( \alpha \) is atomic, the theory produces a canonical \( L^1_{\text{loc}}(X) \)-form \( \sigma \) on \( X \) called the spherical potential such that

\[
\phi(\Omega_F) - \text{Div}(\alpha) = d\sigma.
\]

Furthermore, for each approximation mode there is a smooth family of connections \( D_s, 0 < s \leq \infty \) on \( F \), so that \( \tau_s = \phi(\Omega_s) \) satisfies

\[
\tau_\infty = \phi(\Omega_F) \quad \text{and} \quad \lim_{s \to 0} \tau_s = \text{Div}(\alpha).
\]

There is also a family of \( L^1_{\text{loc}} \)-forms \( \sigma_s \) with \( \lim_{s \to 0} \sigma_s = \sigma \) in \( L^1_{\text{loc}}(X) \) and

\[
\tau_s - \text{Div}(\alpha) = d(\sigma - \sigma_s).
\]

It is useful to view this construction on the total space of the bundle \( \pi : F \to X \). Consider the pull back \( F = \pi^* F \) with the pull back connection. Over \( F \) there is a tautological cross section \( \alpha \) of \( F \) given by \( \alpha(v) = v \). This section is atomic, and the theory applies. Each approximation mode \( \chi \) gives a smooth family of closed differential forms \( \tau_s \), \( 0 < s \leq \infty \) on \( F \), which are expressed canonically in terms of the connection, and which represent the Thom class of \( F \). For example, when \( F \) is real of dimension \( 2n \) and \( \chi(t) = 1 - 1/\sqrt{1 + t} \), \( \tau_s \) is given by the formula

\[
\tau_s = \frac{s}{\sqrt{|u|^2 + s^2}} \tilde{\text{Pf}} \left( \frac{Du^t Du}{|u|^2 + s^2} - \Omega_F \right)
\]

where \( u \) represents the tautological section and \( Du \) is its covariant derivative.
Theorem B. For any approximation mode the form $\tau_s$ is a closed $2n$-form on $F$ which dies at infinity, is integrable on the fibres with integral one, restricts to be $\text{Pf} (\Omega_F)$ on $X$, converges as $s \to 0$ to the current $[X]$ represented by the zero-section, and converges as $s \to \infty$ to $\tilde{\text{Pf}} (\Omega_F)$.

The Thom form $\tau_s$ can be written as the Chern-Weil image of a universal form in the equivariant de Rham complex of $\mathbf{R}^m$. In each approximation mode there is an explicit universal formula for the Thom forms $\tau_s$. If $\chi(t) \equiv 1$ for $t \geq 1$, we have $\text{supp}(\tau_s) \subset \{ v \in F : |v| \leq s \}$. In particular, $\tau_s$ has compact support in each fibre.

There are analogous Thom forms associated to the top Chern form when $F$ is complex.

5. Rectifiable Grothendieck-Riemann-Roch

Another basic formula arises from the theory when considering an atomic section $\alpha \in \Gamma(V)$ of an even-dimensional, real vector bundle $V \longrightarrow X$ with spin structure. Clifford multiplication by $\alpha$ determines a bundle map $\alpha : \mathcal{S}^+ \longrightarrow \mathcal{S}^-$ between the positive and negative complex spinor bundles of $V$. Consider the function on matrices $\text{ch}(A) \overset{\text{def}}{=} \text{trace} \{ \exp(\frac{1}{2\pi i}A) \}$ which gives the Chern character. Suppose $\mathcal{S}^+$ and $\mathcal{S}^-$ carry connections induced from a metric connection on $V$, and let $\Omega_{\mathcal{S}^+}$, $\Omega_{\mathcal{S}^-}$ denote the curvature matrices of these connections.

Theorem C. The following equation of forms and currents holds on $X$:

$$\text{ch}(\Omega_{\mathcal{S}^+}) - \text{ch}(\Omega_{\mathcal{S}^-}) = \tilde{\text{A}}(\Omega_V)^{-1} \text{Div}(\alpha) + dT$$

where

$$\tilde{\text{A}}(\Omega_V)^{-1} = \text{det}^\frac{1}{2} \left\{ \frac{\sinh(\frac{1}{4\pi} \Omega_V)}{\frac{1}{4\pi} \Omega_V} \right\}$$

is the series of differential forms on $X$ which canonically represent, via Chern-Weil Theory, the inverse $\tilde{\text{A}}$-class of $V$, and $T = \tilde{\text{A}}^{-1}(\Omega_V)\sigma$ where $\sigma$ is the spherical potential. More generally, for any complex bundle $E$ with connection over $X$ and $T = \text{ch}(\Omega_E)\tilde{\text{A}}^{-1}(\Omega_V)\sigma$ one has:

$$\text{ch}(\Omega_{\mathcal{S}^+} \otimes E) - \text{ch}(\Omega_{\mathcal{S}^-} \otimes E) = \text{ch}(\Omega_E)\tilde{\text{A}}(\Omega_V)^{-1} \text{Div}(\alpha) + dT.$$
for any vector bundle with connection $E$ over $Y$. By passing to cohomology, this formula yields the commutativity of the diagram
\[
\begin{array}{ccc}
K(Y) & \xrightarrow{j_!} & K(X) \\
\downarrow \text{ch}(\cdot) \wedge \text{Todd}(Y) & & \downarrow \text{ch}(\cdot) \wedge \text{Todd}(X) \\
H^*(Y) & \xrightarrow{j_!} & H^*(X)
\end{array}
\]
where the $j_!$ represent the Gysin "wrong way" maps in K-theory and cohomology.

In these special Clifford multiplication cases this formalism has some similarities with Quillen's calculus of superconnections [Q] as developed in [MQ, BV, BGS*] and elsewhere. However, even in these cases there are substantial differences. We are concerned with transgressions and convergence questions under the weak atomic hypothesis and with the explicit structure of the limiting currents. Our theory also allows for a quite general choice of approximation mode. Choosing $\chi(t) = 1 - e^t$ puts us closest to Quillen's theory. However, choosing $\chi$ with $\chi(t) \equiv 1$ for $t \geq 1$ gives approximations supported in small neighborhoods of the singular set. Approximations where $\chi(t) = t/(1 + t)$ admit nice compactifications (see [Z1]) and are related to MacPherson's Grassmann graph construction.

6. Quaternionic line bundles

Let $\alpha : E \to F$ be an endomorphism of smooth quaternionic line bundles. The classifying space for quaternionic line bundles is the infinite quaternionic projective space $\mathbb{P}^\infty(H)$ whose cohomology is a polynomial ring on one generator $u \in H^2(\mathbb{P}^\infty(H); \mathbb{Z})$ called the instanton class.

**Theorem D.** Suppose $E$ and $F$ are provided with connections which are compatible with the quaternionic structure, and assume that $\alpha$ is atomic. Then for each $\phi \in R[u]$ there exists a canonical $L^1_{\text{loc}}(X)$-form $T$ with the property that
\[
\phi(f) - \phi(e) = \left\{ \frac{\phi(f) - \phi(e)}{f - e} \right\} \text{Div}(\alpha) + dT
\]
where
\[
f = \frac{1}{16\pi^2} \text{tr} \{\Omega_F^2\} \quad \text{and} \quad e = \frac{1}{16\pi^2} \text{tr} \{\Omega_E^2\}
\]
are the canonical representatives of the instanton class of $E$ and $F$.

7. Degeneracy currents

For each bundle map $\alpha : E \to F$ and integer $k$ with $k < m = \text{rank}(E) \leq n = \text{rank}(F)$, we define a current which measures the locus where $\text{rank}(\alpha) \leq k$. Specifically, let $\xi : G_r(E) \to X$ be the Grassmann bundle of $r$-planes in $E$ with $r = m - k$, and let $U \to G_r(E)$ be the tautological $r$-plane bundle. Note that $U$ is a subbundle of $\xi^*E$ and that $\alpha$ pulls back to a bundle map $\xi^*\alpha : \xi^*E \to \xi^*F$. We say that the bundle map $\alpha$ is $k$-atomic if the restriction $\hat{\alpha} = \xi^*\alpha|_U$ is an atomic section of $\text{Hom}(U, \xi^*F)$ over $G_r(E)$. Under this hypothesis we define the $k$th degeneracy current of $\alpha$ to be the current push-forward
\[
\mathbb{D}_k(\alpha) = \xi_* \text{Div}(\hat{\alpha}).
\]
When $\alpha$ is algebraic, $D_k(\alpha)$ is a cycle whose class in the Chow ring $A^*(X)$ is the one defined by Fulton in [Fu]. For given connections on $E$ and $F$ there are canonical families of smooth forms $TP_s$ and $L^1_{\text{loc}}$-forms $S_s$ on $X$, for $0 < s \leq \infty$, such that

$$D_k(\alpha) = TP_s + dS_s$$

where $\lim_{s \to 0} S_s = 0$ in $L^1_{\text{loc}}$ and in the complex case

$$TP_\infty = \det m \times m((c(E - F)_{n-i+j})).$$

Here $c(E - F) \overset{\text{def}}{=} 1 + c_1 + c_2 + \cdots = c(\Omega_F)/c(\Omega_E)$ in the ring of even forms on $X$. There is an analogous formula in the real case. These Thom-Porteous families $TP_s$ are established in [HL2].

8. Geometric formulas

The results above give a wide variety of formulas relating characteristic forms to singularities of maps. For example, consider $\alpha : C^{k+1} \to F$ corresponding to $(k+1)$-sections $s_0, \ldots, s_k$ of a complex bundle with connection $F$. If $\alpha$ is $k$-atomic, the top degeneracy current $D_k(\alpha) \overset{\text{def}}{=} LD(s_0, \ldots, s_k)$ is defined and measures the locus of linear dependence of these sections. From (7) we have

$$c_{n-k}(\Omega_F) - LD(s_0, \ldots, s_k) = dT$$

where $T$ is a canonical $L^1_{\text{loc}}$-form on $X$. There are corresponding formulas for higher-order degeneracies.

A fundamental case occurs when $\alpha = df : TX \to f^*TY$ is the differential of a smooth map $f : X \to Y$ between manifolds. This yields, for example, a $C^\infty$-version of the formula for the global Milnor current (cf. [Fu, 14.1.5]). When $X$ and $Y$ are oriented 4-manifolds, it yields a formula relating $f^*p_1(Y) - p_1(X)$ to a weighted sum of isolated “singular points” where rank$(df) = 2$ (cf. [M2] and [R]). There are also formulas of type (7) explicitly relating Pontrjagin forms to the singularities of projections $X^n \subset \mathbb{R}^{n+n'} \to \mathbb{R}^k$.

Applications to CR-geometry include the following. Consider a generic smooth map $f : M \to \mathbb{C}^{k+1}$ of an oriented riemannian $n$-manifold $M$ where $n - k = 2\ell > 0$. Then there are formulas

$$p_\ell(\Omega_M) = (-1)^\ell \mathbb{C}r(f) + dT$$

where $p_\ell(\Omega_M)$ is the $\ell$th Pontrjagin form of $M$ and where $\mathbb{C}r(f)$ is a current associated to the CR critical set: $\{ x \in M : df : TM \otimes_{\mathbb{R}} \mathbb{C} \to \mathbb{C}^{k+1} \text{ is not surjective} \}$. For example, if dim $M = 4$ and $f : M \to \mathbb{C}^2$ is an immersion, then we have the formula

$$p_1(\Omega_M) = -\mathbb{C}r(f) + dT$$

where $\mathbb{C}r(f)$ is the (generically finite) set of complex tangencies to $f(M) \subset \mathbb{C}^3$ taken with appropriate indices. More complicated formulas involving higher-order complex tangencies and Shur functions are derived in [HL2].

Another application associates geometric currents to pairs of complex structures. Suppose $J_1$ and $J_2$ are smooth almost complex structures on a vector bundle $E \to \cdots$
$X$, and let $E \otimes C = E_1 \oplus E_2$ be the associated splittings. Restriction and projection give a complex bundle map $p : E_1 \rightarrow E_2$ to which there are associated degeneracy currents and geometric formulas. For example, let $n = \text{rank}(E)$ and suppose $\lambda \text{ def } = \Lambda^n \otimes p$ is atomic. Then we have the characteristic current

$$C_r(J_1, J_2) = \text{Div}(\lambda)$$

which is supported in the set \{ $x \in X : \ker(J_1 + J_2) \neq \{0\}$ \}. Let $D_k$ be a connection on $E$ such that $D_k(J_k) = 0$, and set $\varepsilon_k = c_1(D_k)$ for $k = 1, 2$. Then for any $\phi(t) \in C[t]$, there is an $L^1_{\text{loc}}$ form $\sigma_\phi$ on $X$ such that

$$\phi(\varepsilon_2) - \phi(\varepsilon_1) = \frac{\phi(\varepsilon_2) - \phi(\varepsilon_1)}{\varepsilon_2 - \varepsilon_1} C_r(J_1, J_2) + d\sigma_\phi.$$

Similar formulas, which involve the higher degeneracy currents, are derived in [HL2].

The theory produces formulas of the above type in the theory of foliations. It is also possible, using this theory, to rederive and generalize formulas of Sid Webster [W*]. It should be remarked that discussions with Jon Wolfson (cf. [Wo] and [MW]) about Webster’s formulas served as an inspiration for this work.

Each geometric formula discussed in [HL2] carries with it a smooth 1-parameter family of analogous formulas coming from $D_s$. As $s \rightarrow 0$, the characteristic forms converge to the degeneracy current.

In [HL3] the authors study residue formulas associated to bundle maps of general rank. These formulas simultaneously involve several of the degeneracy strata of the map, each paired with its own residue form. They promote the work of R. MacPherson [M1, M2] to the level of characteristic forms and currents.

The authors are indebted to Bill Fulton and John Zweck for important suggestions and comments related to this work.

**References**

[AH] M. F. Atiyah and F. Hirzebruch, *The Riemann-Roch theorem for analytic embeddings*, Topology 1 (1962), 151–166.

[BGS1] J.-M. Bismut, H. Gillet, and C. Soulé, *Analytic torsion and holomorphic determinant bundles. I, II, III*, Comm. Math. Physics 115 (1988), 49–78, 79–126, 301–351.

[BGS2] ———. *Bott-Chern currents and complex immersions*, Duke Math. J. 60 (1990), 255–284.

[BGS3] ———. *Complex immersions and Arakelov geometry*, Grothendieck Festschrift I, Birkhäuser, Boston, 1990, pp. 249–331.

[BV] N. Berline and M. Vergne, *A computation of the equivariant index of the Dirac operator*, Bull. Soc. Math. France 113 (1985), 305–345.

[C1] S. Chern, *A simple intrinsic proof of the Gauss-Bonnet formula for closed Riemannian manifolds*, Ann. of Math. (2) 45 (1944), 747–752.

[C2] ———. *On the curvature integral in a Riemannian manifold*, Ann. of Math. (2) 46 (1945), 674–684.

[F] H. Federer, *Geometric measure theory*, Springer-Verlag, New York, 1969.

[Fu] W. Fulton, *Intersection theory*, Ergeb. Math. Grenzgeb. (3), bd. 2, Springer-Verlag, Berlin and Heidelberg, 1984.

[HL1] F. R. Harvey and H. B. Lawson, Jr., *A theory of characteristic currents associated with a singular connection*, Astérisque 213 (1993), 1–268.

[HL2] ———. *Geometric residue theorems*, MSRI Preprint, 1993, pp. 1–53.

[HL3] ———. *A theory of characteristic currents associated with a singular connection — Part II*, in preparation.
F. R. Harvey and J. Polking, *Fundamental solutions in complex analysis, Part I*, Duke Math. J. 46 (1979), 253–300.

F. R. Harvey and S. Semmes, *Zero divisors of atomic functions*, Ann. of Math. (2) 135 (1992), 567–600.

R. MacPherson, *Singularities of vector bundle maps*, Proceedings of Liverpool Singularities Symposium, I, Lecture Notes in Math., vol. 192, Springer-Verlag, New York, 1971, pp. 316–318.

F. R. Harvey and S. Semmes, *Zero divisors of atomic functions*, Ann. of Math. (2) 135 (1992), 567–600.

R. MacPherson, *Singularities of vector bundle maps*, Proceedings of Liverpool Singularities Symposium, I, Lecture Notes in Math., vol. 192, Springer-Verlag, New York, 1971, pp. 316–318.

V. Mathai and D. Quillen, *Superconnections, Thom classes, and equivariant differential forms*, Topology 25 (1986), 85–110.

M. Micallef and J. Wolfson, *The second variation of area of minimal surfaces in four-manifolds*, Math. Ann. 295 (1993), 245–267.

D. Quillen, *Superconnections and the Chern character*, Topology 24 (1985), 89–95.

F. Ronga, *Le calcul de la classe de cohomologie duale a Σ*, Proceedings of Liverpool Singularities Symposium, I, Lecture Notes in Math., vol. 192, Springer-Verlag, New York, 1971, pp. 313–315.

S. Webster, *Minimal surfaces in a Kähler surface*, J. Differential Geom. 20 (1984), 463–470.

S. Webster, *The Euler and Pontrjagin numbers of an n-manifold in $\mathbb{C}^n$*, Comment. Math. Helv. 60 (1985), 193–216.

S. Webster, *On the relation between Chern and Pontrjagin numbers*, Contemp. Math. 49 (1986), 135–143.

J. Wolfson, *Minimal surfaces in Kähler surfaces and Ricci curvature*, J. Differential Geom. 29 (1989), 281–294.

J. Zweck, *Chern currents of singular connections associated with a section of a compactified bundle*, 1–40 (to appear).

J. Zweck, *Euler and Pontrjagin currents of a section of a compactified real bundle*, 1–32 (to appear).

Department of Mathematics, Rice University, Houston, Texas 77251-1892

Department of Mathematics, SUNY at Stony Brook, Stony Brook, New York 11794-3651