A set on which the local Lojasiewicz exponent is attained

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Abstract. Let $U$ be a neighbourhood of $0 \in \mathbb{C}^n$. We show that for a holomorphic mapping $F = (f_1, \ldots, f_m) : U \to \mathbb{C}^m$, $F(0) = 0$, the Lojasiewicz exponent $L_0(F)$ is attained on the set \{ $z \in U : f_1(z) \cdot \ldots \cdot f_m(z) = 0$ \}.

1. Introduction. In the paper [CK2] the authors showed that for a polynomial mapping $F = (f_1, \ldots, f_m) : \mathbb{C}^n \to \mathbb{C}^m$, $n \geq 2$, the Lojasiewicz exponent $L_\infty(F)$ of $F$ at infinity is attained on the set \{ $z \in \mathbb{C}^n : f_1(z) \cdot \ldots \cdot f_m(z) = 0$ \}. The purpose of this paper is to prove an analogous result for the Lojasiewicz exponent $L_0(F)$, where $F : U \to \mathbb{C}^m$ is a holomorphic mapping, $F(0) = 0$ and $U$ is a neighbourhood of $0 \in \mathbb{C}^n$ (Thm 1). From this result we easily obtain a strict formula for $L_0(F)$ in the case $n = 2$ and $m \geq 2$ in terms of multiplicities of some mappings from $U$ into $\mathbb{C}^2$ defined by components of $F$ (Thm 2). It is a generalization of Main Theorem from [CK1]. Proof of this theorem has been simplified by A. Ploski in [P]. His proof has been an inspiration to write this paper.

Theorem 1 is an important tool for investigation of the Lojasiewicz exponent for analytic curves having an isolated intersection point at $0 \in \mathbb{C}^n$. Using it, we shall give in the next paper [CK3], an effective formula for the Lojasiewicz exponent for such curves in terms of their parametrizations.

2. The Lojasiewicz exponent. Let $U \subset \mathbb{C}^n$, $n \geq 2$, be a holomorphic mapping, $F : U \to \mathbb{C}^m$ a holomorphic mapping, $S \subset U$ an analytic set in $U$. Assume that $0 \in \mathbb{C}^n$ is an accumulation point of $S$. Put

$$N(F|S) := \{ \nu \in \mathbb{R}_+ : \exists A > 0, \exists B > 0, \forall z \in S, |z| < B \Rightarrow A|z|^\nu \leq |F(z)| \}.$$  

Here $|\cdot|$ means the polycylindric norm. If $S = U$ we write $N(F)$ instead of $N(F|U)$.

By the Lojasiewicz exponent of the mapping $F|S$ at 0 we mean

$$L_0(F|S) := \inf N(F|S).$$

Analogously $L_0(F) := \inf N(F)$.

It can be shown (cf [LT], §§5,6)

Proposition 1. If $F|S$ has an isolated zero at $0 \in \mathbb{C}^n$, then $L_0(F|S) \in N(F|S) \cap \mathbb{Q}$. Moreover, there exists an analytic complex curve $\varphi : \{ t \in \mathbb{C} : |t| < r \} \to S$ such that $\varphi(0) = 0$ and

$$|F \circ \varphi(t)| \sim |\varphi(t)|^{L_0(F|S)} \quad \text{for } t \to 0.$$  

From the above proposition we easily get

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Corollary 1. \( \mathcal{L}_0(F|S) < \infty \) if and only if \( F|S \) has an isolated zero of \( 0 \in \mathbb{C}^n \).

3. The main result. Now, we shall give the main result of this paper.

Theorem 1. Let \( U \subset \mathbb{C}^n, n \geq 2, \) be a neighbourhood of the origin, \( F = (f_1, \ldots, f_m) : U \to \mathbb{C}^m \) a holomorphic mapping, and \( F(0) = 0 \). Define \( S := \{ z \in U : f_1(z) \cdot \ldots \cdot f_m(z) = 0 \} \). Then

\[
\mathcal{L}_0(F) = \mathcal{L}_0(F|S).
\]

The proof will be given in section 4.

Immediately from Theorem 1 we obtain an effective formula for the Lojasiewicz exponent in the case \( n = 2, m \geq 2 \), generalizing an earlier authors' result ([CK1], Main Thm).

Let us begin with notations. Let \( U \) be a neighbourhood of \( 0 \in \mathbb{C}^2 \). Then: \( \mu(f,g) \) means the intersection multiplicity of a holomorphic mapping \( (f,g) : U \to \mathbb{C}^2; \hat{h} \) means the germ of a holomorphic function \( h : U \to \mathbb{C} \) in the ring \( \mathcal{O}^2 \) of germs of holomorphic functions at \( 0 \in \mathbb{C}^2; \text{ord} \hat{h} \) means the order of \( h \) at \( 0 \in \mathbb{C}^2 \).

Theorem 2. Let \( U \subset \mathbb{C}^2 \) be a neighbourhood of the origin, \( F = (f_1, \ldots, f_m) : U \to \mathbb{C}^m \) a holomorphic mapping, \( F(0) = 0 \). Put \( \hat{f} := f_1 \cdot \ldots \cdot f_m \). If \( \hat{f} \neq 0 \) and \( \hat{f} = h_1 \cdot \ldots \cdot h_r \) is a factorization of \( \hat{f} \) into irreducible germs in \( \mathcal{O}^2 \), then

\[
\mathcal{L}_0(F) = \max_{i=1}^r \frac{1}{\text{ord} h_i} \min_{j=1}^m \mu(h_i, f_j).
\]

Proof. Since our considerations are local, we may assume that \( h_i \) are holomorphic in \( U \) and \( f = h_1 \cdot \ldots \cdot h_r \) in \( U \). Let \( S := \{ z \in U : f(z) = 0 \} \) and \( \Gamma_i := \{ z \in U : h_i(z) = 0 \} \). Hence

\[
S = \Gamma_1 \cup \ldots \cup \Gamma_r.
\]

Define \( \lambda_i := (1 / \text{ord} h_i) \min_{j=1}^m \mu(h_i, f_j) \). If \( \lambda_i = +\infty \) for some \( i \), then (3) holds. So, assume that \( \lambda_i \neq +\infty, i = 1, \ldots, r \). Then for every \( i \) we have

\[
|F(z)| \sim |z|^{\lambda_i} \quad \text{for } |z| \to 0 \text{ and } z \in \Gamma_i.
\]

Hence and from (4), \( \mathcal{L}_0(F|S) = \max_{i=1}^r \lambda_i \). This and Theorem 1 give (3), which ends the proof.

4. Proof of the main theorem. The proof is given in two steps. In the first one we give the proof under some additional assumptions, whereas in the second one, we show that these assumptions do not restrict our considerations.

First we fix some notations. For \( z = (z_1, \ldots, z_n) \in \mathbb{C}^n, n \geq 2, \) and for every \( i \in \{1, \ldots, n\} \) we put \( z_i' := (z_1, \ldots, z_{i-1}, \bar{z}_{i+1}, \ldots, z_n) \). Additionally, we define \( f := f_1 \cdot \ldots \cdot f_m \).

Step 1. We assume that

(i) \( (F|S)^{-1}(0) = \{0\} \),
(ii) \( \text{ord} f < \infty \),
(iii) for every \( i \in \{1, \ldots, n\} \), \( f \) is \( (\text{ord} f) \)-regular with respect to \( z_i \).
Obviously \( N(F) \subset N(F|S) \). To show (2) it suffices to prove

\[
N(F|S) \subset N(F).
\]

It follows from (i) and Corollary 1 that \( N(F|S) \) is not empty. Take an arbitrary \( \nu \in N(F|S) \). Then there exist \( A, B > 0 \) such that

\[
|F(\zeta)| \geq A|\zeta|^r \quad \text{for} \quad \zeta \in S, \ |\zeta| < B.
\]

From the assumptions of the theorem we have \( \text{ord} f > 0 \) and \( \text{ord} f_j > 0, \ j = 1, \ldots, m \). Then from (ii), (iii) we easily get \( 0 < \text{ord} f_j < \infty \) and

\[
 \text{for every } i, j, f_j \text{ is (ord } f_j \text{-regular with respect to } z_i. \]

The Weierstrass Preparation Theorem and (iii) imply that for every \( i \in \{1, \ldots, n\} \) there exists a Weierstrass polynomial with respect to \( z_i \) of degree \( \text{ord} f \), associated with \( f \). Denote it by \( p^{(i)} \). Analogously from (7) for every \( i \) there exists a Weierstrass polynomial with respect to \( z_i \) of degree \( \text{ord} f_j \), associated with \( f_j \). Denote it by \( p^{(i)}_j \). Then there exist \( C, D > 0 \) and a polydisc \( \{ z \in C^n : |z| < r \} \subset U \) such that

\[
|p^{(i)}(z)| \leq |f(z)| \leq D|p^{(i)}(z)| \quad \text{for} \quad |z| < r, \ i = 1, \ldots, n,
\]

and

\[
|p^{(i)}_j(z)| \leq |f_j(z)| \leq D|p^{(i)}_j(z)| \quad \text{for} \quad |z| < r, \ i = 1, \ldots, n, \ j = 1, \ldots, m.
\]

Put \( P^{(i)} := (p^{(i)}_1, \ldots, p^{(i)}_m) \). Then from (9) we get

\[
|C|P^{(i)}(z)| \leq |F(z)| \leq D|P^{(i)}(z)| \quad \text{for} \quad |z| < r, \ i = 1, \ldots, n.
\]

Clearly, for every \( i \in \{1, \ldots, n\} \)

\[
p^{(i)} = p^{(i)}_1 \cdots p^{(i)}_m.
\]

Put \( B_1 := \min(B, r) \). Then from (8) we have for every \( i \in \{1, \ldots, n\} \)

\[
S \cap \{ z \in C^n : |z| < B_1 \} = \{ z \in C^n : |z| < B_1, \ p^{(i)}(z) = 0 \}.
\]

Hence and from the Theorem on Continuity of Roots, applied to \( p^{(i)} \), we get that there exists \( \varrho, 0 < \varrho \leq B_1 \), such that for every \( i \in \{1, \ldots, n\} \) we have

\[
\{ z \in S : |z'_i| < \varrho, \ |z| < B_1 \} = \{ z \in C^n : |z'_i| < \varrho, \ p^{(i)}(z) = 0 \}.
\]

Put \( d := \max_{j=1}^m \text{ord } f_j, \ A_2 := 2^{-d}A(C/D), \ B_2 := \min(\varrho, B_1) \). Take an arbitrary \( \tilde{z} \in C^n, \ |\tilde{z}| < B_2 \). There exists \( i \in \{1, \ldots, n\} \) such that \( |\tilde{z}| = |z'_i| \).

Define \( \varphi_j(t) := p^{(i)}_j(\tilde{z}_1, \ldots, \tilde{z}_{i-1}, t, \tilde{z}_{i+1}, \ldots, \tilde{z}_n), \ \Phi := (\varphi_1, \ldots, \varphi_m) \). Clearly, \( \Phi :
\( \mathbb{C} \to \mathbb{C}^m \) is a polynomial mapping, \( \deg \Phi := \max_{j=1}^{m} \deg \varphi_j = d \) and \( \Phi(t) = P^{(i)}(\hat{z}_1, \ldots, \hat{z}_{i-1}, t, \hat{z}_{i+1}, \ldots, \hat{z}_n) \). Then by Lemma 2 in \([\text{CK}_2] \) and (11) we have
\[
|\Phi(\hat{z}_i)| \geq 2^{-d} \min_{\tau \in T} |\Phi(\tau)|,
\]
where \( T := \{ t \in \mathbb{C} : p^{(i)}(\hat{z}_1, \ldots, \hat{z}_{i-1}, t, \hat{z}_{i+1}, \ldots, \hat{z}_n) = 0 \} \). Hence and from (10) we get
\[
|F(\hat{z})| \geq C|P^{(i)}(\hat{z})| = C|\Phi(\hat{z}_i)| \geq C2^{-d}|\Phi(\tau_0)|
\]
\[
= C2^{-d}|P^{(i)}(\hat{\zeta})| \geq (C/D)2^{-d}|F(\hat{\zeta})|
\]
for some \( \hat{\zeta} = (\hat{z}_1, \ldots, \hat{z}_{i-1}, \tau_0, \hat{z}_{i+1}, \ldots, \hat{z}_n) \) such that \( p^{(i)}(\hat{\zeta}) = 0 \). Since \( |\hat{\zeta}'| = |\hat{z}'| = |\hat{z}| < B_2 \leq \rho \), then from (12) we have \( \hat{\zeta} \in S \) and \( |\hat{\zeta}| < B_1 \). In consequence, from (6) and (13) we get
\[
|F(\hat{z})| \geq (C/D)2^{-d}A|\hat{\zeta}'|^{\nu} \geq A_2|\hat{\zeta}'|^{\nu} = A_2(|\hat{z}|)^{\nu}.
\]
Since \( \hat{z} \) is arbitrary we obtain \( \nu \in N(F) \). This ends the proof of the theorem under assumptions (i), (ii), (iii).

Step 2. Now, we shall prove the theorem in the remaining cases. If (i) does not hold, then by Corollary 1 we have \( \mathcal{L}_0(F|S) = \mathcal{L}_0(F) = \infty \), that is, (2) is satisfied. If (ii) does not hold, then \( S = U \) and (2) is obvious. So, it suffices to consider the case when (i), (ii) hold but (iii) does not. Since \( N(F) \) and \( N(F|S) \) are invariant with respect to linear automorphisms of \( \mathbb{C}^n \), then \( \mathcal{L}_0(F) \) and \( \mathcal{L}_0(F|S) \) are also invariant of such automorphisms. Since the considered case can be reduced to step 1 by a linear automorphism of \( \mathbb{C}^n \) then (2) also holds in this case.

This ends the proof of the theorem.

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