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S-integral points on elliptic curves - Notes on a paper of B. M. M. de Weger

par EMANUEL HERRMANN * et ATTILA PETHŐ **

RÉSUMÉ. Nous donnons une nouvelle preuve beaucoup plus courte d'un résultat de B. M. M de Weger. Cette preuve est basée sur la théorie des formes linéaires de logarithmes complexes, p-adiques et elliptiques, pour lesquelles nous obtenons une majoration en confrontant les résultats de Hajdu et Herendi à ceux de Rémond et Urfels.

ABSTRACT. In this paper we give a much shorter proof for a result of B.M.M de Weger. For this purpose we use the theory of linear forms in complex and p-adic elliptic logarithms. To obtain an upper bound for these linear forms we compare the results of Hajdu and Herendi and Rémond and Urfels.

1. Introduction

In a recent paper [12] B.M.M. de Weger solved the Diophantine equation

$$y^2 = x^3 - 228x + 848 \tag{1}$$

completely in rational numbers x, y such that their denominator in the lowest form is a power of 2. With other words, he solved (1) in S-integers where $S = \{2, \infty\}$. De Weger uses in the proof algebraic number theoretical considerations and lower estimates for linear forms in complex and q-adic logarithms of algebraic numbers.

In the present paper we will give a much shorter proof of a generalization of Theorem 1 of [12]. Here we use the theory of elliptic curves and linear forms in elliptic logarithms. More precisely, we are using a theorem of Rémond and Urfels [6], which can be applied for curves of rank at most 2. An alternative method which avoids lower bounds for linear forms in q-adic elliptic logarithms is given in [5]. However the bounds coming from [5] are

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in the actual case much larger as working directly with the Theorem of Rémond and Urfels (cf. Section 3).

We now state our result.

Theorem 1. *Let* $S = \{2, 3, 5, 7, \infty\}$. *Then the equation*

$$y^2 = x^3 - 228x + 848$$

has only 65 *S-integer solutions* $(x, \pm y)$ *listed in Table 2 at the end of this paper.*

2. Notations and Auxiliary Results

Let the elliptic curve be defined by the equation

$$y^2 = x^3 + Ax + B, \qquad A, B \in \mathbb{Z}. \tag{2}$$

Let $S = \{q_1, \ldots, q_{s-1}, q_s = \infty\}$ be a set of primes including the infinite prime. To simplify the presentation we assume that the equation (2) is minimal for every finite prime $q \in S$. For the general case we refer to the paper [5].

Let $P_1, \ldots, P_r$ denote a basis of the Mordell-Weil group $E(\mathbb{Q})$ and let g be the order of the torsion subgroup $E_{\text{tors}}(\mathbb{Q})$ of $E(\mathbb{Q})$. Let $\hat{h}$ denote the Néron-Tate height on $E(\mathbb{Q})$. Designate by λ the smallest eigenvalue of the positive definite regulator matrix $(\hat{h}(P_i, P_j))_{1 \le i,j \le r}$.

Let $\wp(u)$ be the Weierstrass $\wp$-function corresponding to the curve $E(\mathbb{C})$. Let $\Omega = \langle \omega_1, \omega_2 \rangle$ be its fundamental lattice and ω_1 its real period. There exists, for any $P = (x, y) \in E(\mathbb{C})$, an element $u \in \mathbb{C}/\Omega$ such that $(x, y) = (\wp(u), \frac{1}{2}\wp'(u))$. This is called the *(complex) elliptic logarithm* of P. In the sequel $u_{i,\infty}$ denotes the elliptic logarithm of P_i for $i = 1, \ldots, r$. We put $u'_{i,\infty} = g\frac{u_{i,\infty}}{\omega_1}$.

For a finite prime $q \in S$ let $E_0(\mathbb{Q}_q)$ denote the points of $E(\mathbb{Q}_q)$ with non-singular reduction modulo q. Then the index $[E(\mathbb{Q}_q) : E_0(\mathbb{Q}_q)]$ is finite, and equal to the Tamagawa number c_q because by our assumption equation (2) is minimal at q. Let further $\tilde{E}$ denote the reduced curve E modulo q. Let $\mathcal{N}_q = \#\tilde{E}(\mathbb{F}_q)$ be the number of rational points of $\tilde{E}/\mathbb{F}_q$. With the order g of the torsion group, we define the number

$$m = m_q = \operatorname{lcm}(g, c_q \cdot \mathcal{N}_q).$$

Finally for the finite places $q \in S$, let $u'_{i,q}$ denote the q-adic elliptic logarithm of mP_i for $i = 1, \ldots, r$. For the definition and basic properties of q-adic elliptic logarithms we refer to Silverman [7] and to [5]. Now we state the main result of [5] in the special case considered, i.e. for curves given in short Weierstrass form.

Theorem A. *Let the elliptic curve* $E(\mathbb{Q})$ *be defined by equation (2), which is minimal for every finite prime* $q \in S$. *Assume that the S-integral point*

$P = (x, y) \in E(\mathbb{Z}_S)$ has the representation

$$P = \sum_{i=1}^{r} n_i P_i + T \tag{3}$$

with $n_i \in \mathbb{Z}, i = 1, \ldots, r$, and T a torsion point of $E(\mathbb{Q})$. For $N(P) = \max\{|n_i|, i = 1, \ldots, r\}$, we have

$$N(P) \leq N_0 = \sqrt{\tfrac{1}{\lambda}(\tfrac{k_1}{2} + k_2)} \tag{4}$$

with $k_2 = \log \max\{|2A|^{1/2}, |4B|^{1/3}\}$,

$$\begin{aligned} k_1' &= 7 \cdot 10^{38s+49} s^{20s+15} Q^{24} (\log^* Q)^{4s-2} k_3 (\log k_3)^2 ((20s-19)k_3 + \log(ek_4)), \\ k_1 &= k_1' + 2\log 6, \end{aligned}$$

where $\log^* Q = \max\{\log Q, 1\}$ for $Q = \max\{q_1, \ldots, q_{s-1}\}$, $s = \#S$,

$$\begin{aligned} k_3 &= \tfrac{32}{3} \sqrt{|\Delta_0|} \left(8 + \tfrac{1}{2}\log|\Delta_0|\right)^4, \\ k_4 &= 10^4 \max\{16A^2, 256\sqrt{|\Delta_0|}^3\} \end{aligned}$$

with $\Delta_0 = 4A^3 + 27B^2$. Moreover, there exists a place $q \in S$ such that

$$\left| \sum_{i=1}^{r} n_i u'_{i,q} + n_{r+1} \right|_q \leq k_5 \exp\{-\tfrac{\lambda}{s} N(P)^2 + \tfrac{k_2}{s}\} \tag{5}$$

with $n_{r+1} \in \mathbb{Z}$ if $q = \infty$ and $n_{r+1} = 0$ otherwise, and with $k_5 = \frac{2g}{3\omega_1}$ if $q = \infty$ and $k_5 = 1$ otherwise.

Theorem A together with numerical Diophantine approximation techniques is sufficient to prove our Theorem 1. However it was pointed out already in [5] that combining the method of Smart [8] with results of David [2] and of Rémond and Urfels [6] one can obtain a much better estimate for $N(P)$ as by the one implied by Theorem A. In the sequel we assume $r \leq 2$. To formulate the next theorem we have to introduce further notations. Let

$j = \frac{j_1}{j_2}$ with $j_1, j_2 \in \mathbb{Z}$ and $\gcd(j_1, j_2) = 1$ be the j–invariant of $E(\mathbb{Q})$. Put

$$\begin{aligned}
h &= \log \max\{4|Aj_2|, 4|Bj_2|, |j_1|\}, \\
\log V_i &= \max\left\{\hat{h}(P_i), h, \frac{3\pi |u'_{i,\infty}|^2_\infty}{\operatorname{Im}\tau}\right\}, \quad i = 1, 2, \\
\log V_0 &= \max\left\{h, \frac{3\pi}{\operatorname{Im}\tau}\right\}, \\
k_{6,\infty} &= \frac{k_2 + s \log k_5}{\lambda}, \\
k_{7,\infty} &= \frac{2 \cdot 10^{68} \cdot s \cdot h^5}{\lambda} \prod_{i=0}^{2} \log V_i.
\end{aligned}$$

For a finite place $q \in S$ let

$$\begin{aligned}
\alpha_q &= \begin{cases} 3, & \text{if } q = 2 \\ \frac{1}{q-1}, & \text{otherwise} \end{cases} \\
\sigma_q &= (q^{\alpha_q} \max\{|u'_{1,q}|_q, |u'_{2,q}|_q\})^{-1}, \\
d_q &= \max\{1, 1/\log \sigma_q\}, \\
a_i &= \max\{1, \hat{h}(P_i)\}, \quad i = 1, 2, \\
\beta &= \max\{\log N(P), \log |A|_\infty, \log |B|_\infty, a_1, a_2, d_q\}, \\
\gamma &= \max\{\log |A|_\infty, \log |B|_\infty, \log \beta\}, \\
k_{6,q} &= \frac{k_2}{\lambda}, \\
k_{7,q} &\geq (3.6 \cdot 10^{25} s \cdot a_1 a_2 d_q^6 \log \sigma_q)/\lambda.
\end{aligned}$$

Theorem B. *Assuming that $r \leq 2$ and using the notations introduced in Theorem A and above we have*

$$N(P) \leq N_1 := \max\{N_q \,:\, q \in S\},$$

where

$$N_q = \begin{cases} 2^5 \sqrt{k_{6,\infty} k_{7,\infty}} (\log 5^5 k_{7,\infty})^{5/2}, & \text{if } q = \infty, \\ 2^4 \sqrt{k_{6,q} k_{7,q}} (\log 4^4 k_{7,q})^2, & \text{if } q \in S \setminus \{\infty\}. \end{cases}$$

Proof. Combining inequality (5) with the lower bounds for linear forms in elliptic logarithms due to David [2] and for linear forms in at most two q–adic elliptic logarithms due to Rémond and Urfels [6] one obtains the upper bound for $N(P)$ analogously as described for example in Gebel, Pethő and Zimmer [3, 4]. Therefore we omit the details. □

3. Proof of Theorem 1

3.1. Basic data of the elliptic curve. In the sequel we denote by E the elliptic curve over $\mathbb{Q}$ defined by equation (1). Let $S = \{2, 3, 5, 7, \infty\}$. It is easy to check, that (1) is minimal for every finite prime $q \in S$. Actually, it is a global minimal model of E. The discriminant of E is $\Delta = -16\Delta_0$ with $\Delta_0 = -27993600$. We have

$$E(\mathbb{Q}) \simeq \mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}^2,$$

where the only non-trivial torsion point is $(4, 0)$ and a basis of the infinite part of the Mordell-Weil group is $P_1 = (-2, 36), P_2 = (-11, 45)$. (See Tzanakis [10], or one of of the programs apecs [13], Magma[1] [1], mwrank [14] or Simath [15].)

Now we can compute the fundamental parallelogram of the associated Weierstrass $\wp$-function and get

$$\omega_1 = 0.767848, \qquad \omega_2 = -0.631356 \cdot i \quad \text{and} \quad \tau = \tfrac{\omega_1}{\omega_2} = 1.216188 \cdot i.$$

The regulator matrix of E is

$$R = \begin{pmatrix} 0.423441 & -0.158771 \\ -0.158771 & 0.906408 \end{pmatrix},$$

hence its smallest eigenvalue is given by $\lambda = 0.375922$.

Using Tate's algorithm [9] we compute the Tamagawa numbers

$$c_2 = 4, \quad c_3 = 4, \quad c_5 = 2 \quad \text{and} \quad c_7 = 1.$$

The curve E has additive reduction at the primes 2 and 3, multiplicative reduction at 5 and good reduction at 7. Hence,

$$\mathcal{N}_2 = 2, \quad \mathcal{N}_3 = 3, \quad \mathcal{N}_5 = 6 \quad \text{and} \quad \mathcal{N}_7 = 12.$$

Using these data we can compute the numbers m_q and obtain

$$m_2 = 8, \quad m_3 = 12, \quad m_5 = 12 \quad \text{and} \quad m_7 = 12.$$

3.2. Upper Bounds for $N(P)$.

(i) The first way to obtain an upper bound for $N(P)$ is to calculate N_0 of Theorem A. We have actually $Q = 7, s = 5$,

$$\begin{aligned} k_2 &= \log \max\{456^{1/2}, 3392^{1/3}\} = 3.061246, \\ k_3 &= \tfrac{32}{3}\sqrt{|\Delta_0|}\left(8 + \tfrac{1}{2}\log|\Delta_0|\right)^4 = 4.258342 \cdot 10^9, \\ k_4 &= 10^4 \max\{16 \cdot 228^2, 256 \cdot |\Delta_0|^{3/2}\} = 3.791649 \cdot 10^{17} \end{aligned} \tag{6}$$

and $k_1 = 3.730724 \cdot 10^{369}$, hence $N(P) \le N_0 = 7.044216 \cdot 10^{184}$.

(ii) Another, a bit more complicated, way to find an upper bound for $N(P)$ is to compute $N_1 = \max\{N_q \ : \ q \in S\}$ as defined in Theorem B.

[1] Magma version 2.6 will have an implementation of the algorithm described in [5].

Consider first the case $q=\infty$. Then we have

$$\begin{aligned}
h =&\log\max\{4\cdot 228\cdot 75, 4\cdot 848\cdot 75, 2^5\cdot 19^3\} = 12.446663,\\
\log V_0 =&\max\{h, \tfrac{3\pi}{\mathrm{Im}\tau}\} = 12.446663,\\
\log V_1 =&\max\{\hat{h}(P_1), h, \tfrac{3\pi g^2|u_{1,\infty}|_\infty^2}{\omega_1^2\mathrm{Im}\tau}\} = 21.645104,\\
\log V_2 =&\max\{\hat{h}(P_2), h, \tfrac{3\pi g^2|u_{2,\infty}|_\infty^2}{\omega_1^2\mathrm{Im}\tau}\} = 28.279603,\\
k_{5,\infty} =&\tfrac{4}{3\omega_1} = 1.736455,\\
k_{6,\infty} =&15.483196,\\
k_{7,\infty} =&6.054145\cdot 10^{78}.
\end{aligned}$$

Thus we obtain $N_\infty \leq 1.530526\cdot 10^{47}$ after a simple computation.

Next we have to consider the cases $q=2,3,5$ and 7. In Table 1 below you find the actual values of α_q, σ_q and d_q.

Table 1

q	2	3	5	7
α_q	3	1/2	1/4	1/6
σ_q	2	$3^{1/2}$	$5^{3/4}$	$7^{5/6}$
d_q	$1/\log 2$	$2/\log 3$	1	1
$k_{7,q}$	$2.992592\cdot 10^{27}$	$9.5742\cdot 10^{27}$	$5.779766\cdot 10^{26}$	$7.76455\cdot 10^{26}$

The following values are independent of $q\in\{2,3,5,7\}$

$$\begin{aligned}
a_1 &= \max\{1, \hat{h}((-2,36))\} = \max\{1, 0.423441\} = 1,\\
a_2 &= \max\{1, \hat{h}((-11,45))\} = \max\{1, 0.906408\} = 1,\\
k_{6,q} &= k_2/\lambda = 8.143301.
\end{aligned}$$

Choosing the worst cases from Table 1 we see that we can take

$$k_{7,q} = k_{7,3} = 9.5742\cdot 10^{27}, \quad q=2,3,5,7,$$

thus

$$N_q = N_3 = 2.187487\cdot 10^{19}, \quad q=2,3,5,7.$$

These inequalities imply

$$N(P)\leq N_1 = \max\{N_q : q\in S\} = 1.530526\cdot 10^{47}$$

by Theorem B. Since N_1 is much smaller than N_0 we use this value in the sequel.

3.3. Reduction of the large upper bound for $N(P)$. By Theorem 1, and by the last section we have to solve the Diophantine approximation problem

$$\begin{aligned} |n_1 u'_{1,q} + n_2 u'_{1,q} + n_3|_q &\leq k_5 \exp\{0.075184 \cdot N(P)^2 + 0.6122492\}, \\ N(P) &\leq N_1 = 1.530526 \cdot 10^{47} \end{aligned}$$

for each $q \in S$.

To solve these systems we use the well known reduction procedure of de Weger [11]. (See also Smart [8].) For details about the high precision computation of q-adic elliptic logarithms we refer to Pethő et al. [5]. We shall also use the notations introduced there.

We first take $q = \infty$ and perform a de Weger reduction with $C = 10^{142}$. We obtain the new upper bound $N(P) \leq \mathcal{M}_\infty = 67$ in the case $q = \infty$. Comparing this bound with $N_q, q = 2, 3, 5, 7$ we obtain

$$N(P) \leq N_3 = 2.187487 \cdot 10^{19},$$

i.e. we may perform the $q-$adic reduction steps with this value.

To do this we compute for each $q \in S \backslash \{\infty\}$, the q-adic elliptic logarithms of $m_q P_i, i = 1, 2$, with precision at least

$$n_2 = 129, \quad n_3 = 82, \quad n_5 = 56, \quad n_7 = 46.$$

This precision is necessary to carry out the q-adic de Weger reduction. For this purpose we use the method of [5].

$$\begin{aligned} u'_{1,2} &= 134584334573222732131510464853384888320 + O(2^{128}) \\ u'_{2,2} &= 224603122385055121905025779589746548856 + O(2^{128}) \\ u'_{1,3} &= 35130898366670225251067310603381664587 + O(3^{81}) \\ u'_{2,3} &= 32674326287561878726624624078558984866 + O(3^{81}) \\ u'_{1,5} &= 118414103305724592543524002578287458095 + O(5^{55}) \\ u'_{2,5} &= 193714651202697832194263283063279750580 + O(5^{55}) \\ u'_{1,7} &= 49086609441793589144883973076015987885 + O(7^{46}) \\ u'_{2,7} &= 723939447229120403790851561285560713079 + O(7^{46}) \end{aligned}$$

Now we perform the q-adic de Weger reduction with the values $C_2 = 2^{128}$, $C_3 = 3^{81}$, $C_5 = 5^{55}$ and $C_7 = 7^{46}$ and obtain the new bound

$$N(P) \leq \max\{\mathcal{M}_\infty = 67, \mathcal{M}_2 = 12, \mathcal{M}_3 = 13, \mathcal{M}_5 = 13, \mathcal{M}_7 = 13\}.$$

This new upper bound for $N(P)$ can be further reduced. On repeating this reduction process 3-times, we eventually get $N(P) \leq 13$, which cannot be reduced any further.

Table 2

S-integral points $P=(x,y)=\left(\frac{\xi}{\zeta^2},\frac{\eta}{\zeta^3}\right)=\sum_{i=1}^{2} n_i P_i + T_j,\quad j=0,1$ on $E:\ y^2=x^3-228x+848$ for $S=\{2,\ 3,\ 5,\ 7,\ \infty\}$

rank	2
basis	$P_1=(-2,36)$, $P_2=(-11,45)$
torsion	$T_0=\mathcal{O}$, $T_1=(4,0)$

#	ξ	η	ζ	F	(n_1,n_2,j)
1	4	0	1		$(0,0,1)$
2	−11	45	1		$(0,1,0)$
3	16	36	1		$(0,1,1)$
4	94	−900	1		$(1,-1,0)$
5	2	−20	1		$(1,-1,1)$
6	−2	36	1		$(1,0,0)$
7	34	180	1		$(1,0,1)$
8	14	−20	1		$(1,1,0)$
9	−14	−36	1		$(1,1,1)$
10	754	−20700	1		$(1,2,1)$
11	196	2736	1		$(2,-1,1)$
12	13	9	1		$(2,0,0)$
13	−16	20	1		$(2,0,1)$
14	52	−360	1		$(2,1,1)$
15	53	371	1		$(2,2,0)$
16	814	23220	1		$(3,1,0)$
17	534256	−390502764	1		$(4,3,1)$
18	97	−783	2	2	$(0,-2,0)$
19	1	−225	2	2	$(2,1,0)$
20	857	−25027	2	2	$(4,0,0)$
21	49	855	4	2^2	$(2,-1,0)$
22	−16439	−631035	32	2^5	$(2,3,0)$
23	−44	−1160	3	3	$(0,-2,1)$
24	34	172	3	3	$(3,1,1)$
25	1534	42020	9	3^2	$(3,-1,0)$
26	94	−828	5	5	$(1,2,0)$
27	629	−13133	5	5	$(2,-2,0)$
28	−194	−5796	5	5	$(3,0,0)$
29	6361	−282141	20	$2^2\times 5$	$(4,2,0)$
30	−818	−468	7	7	$(1,-2,0)$
31	16	9540	7	7	$(2,2,1)$
32	946	−20700	7	7	$(3,0,1)$
33	8516	1163623840	343	7^3	$(4,-2,1)$

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